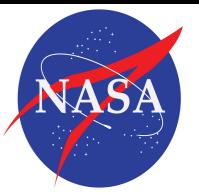
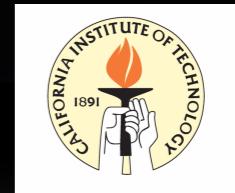


Planet Formation in Star-Forming Regions

: from the Solar System to Other Worlds



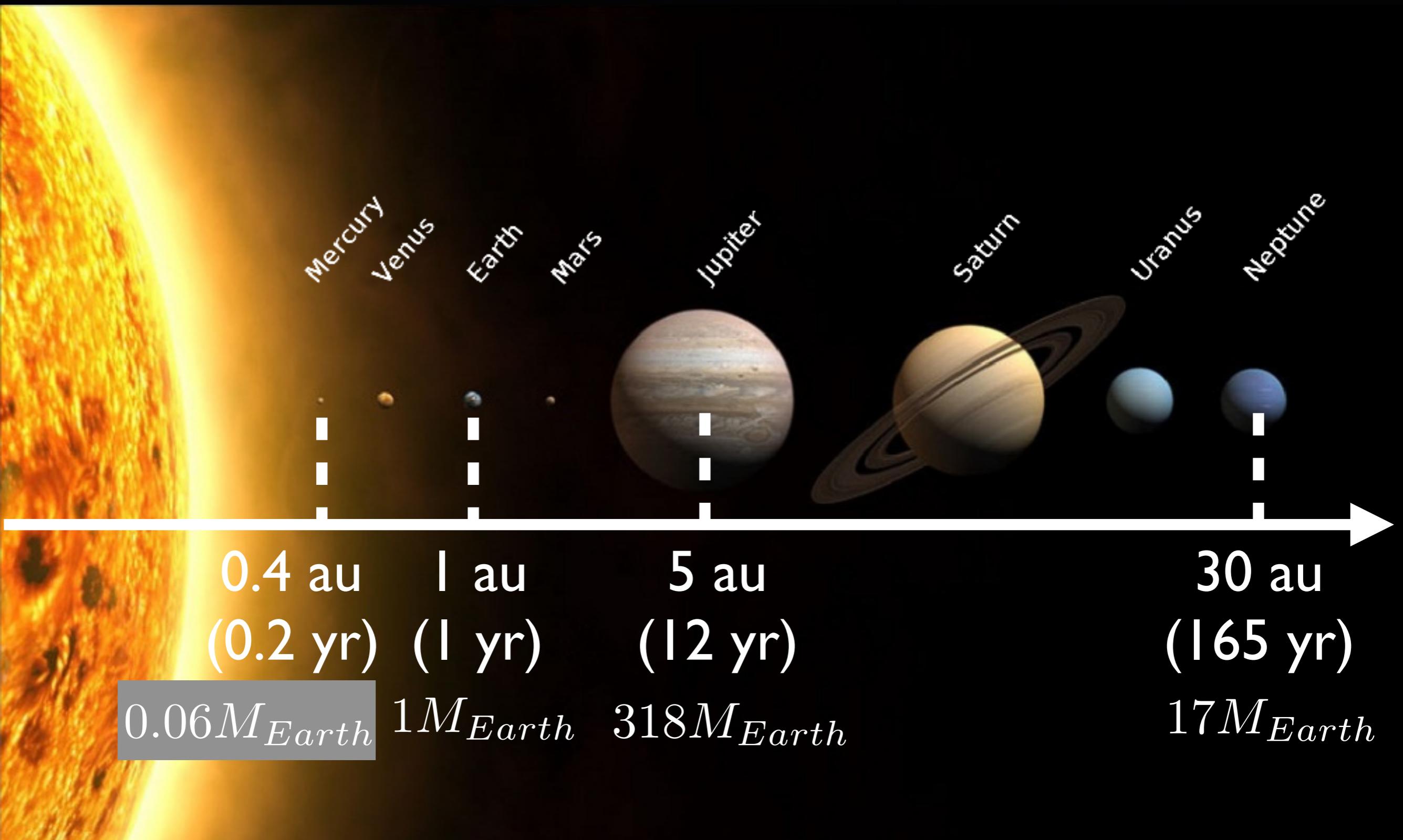
Yasuhiro Hasegawa

Jet Propulsion Laboratory,
California Institute of Technology

Best Example of Planetary Systems

???

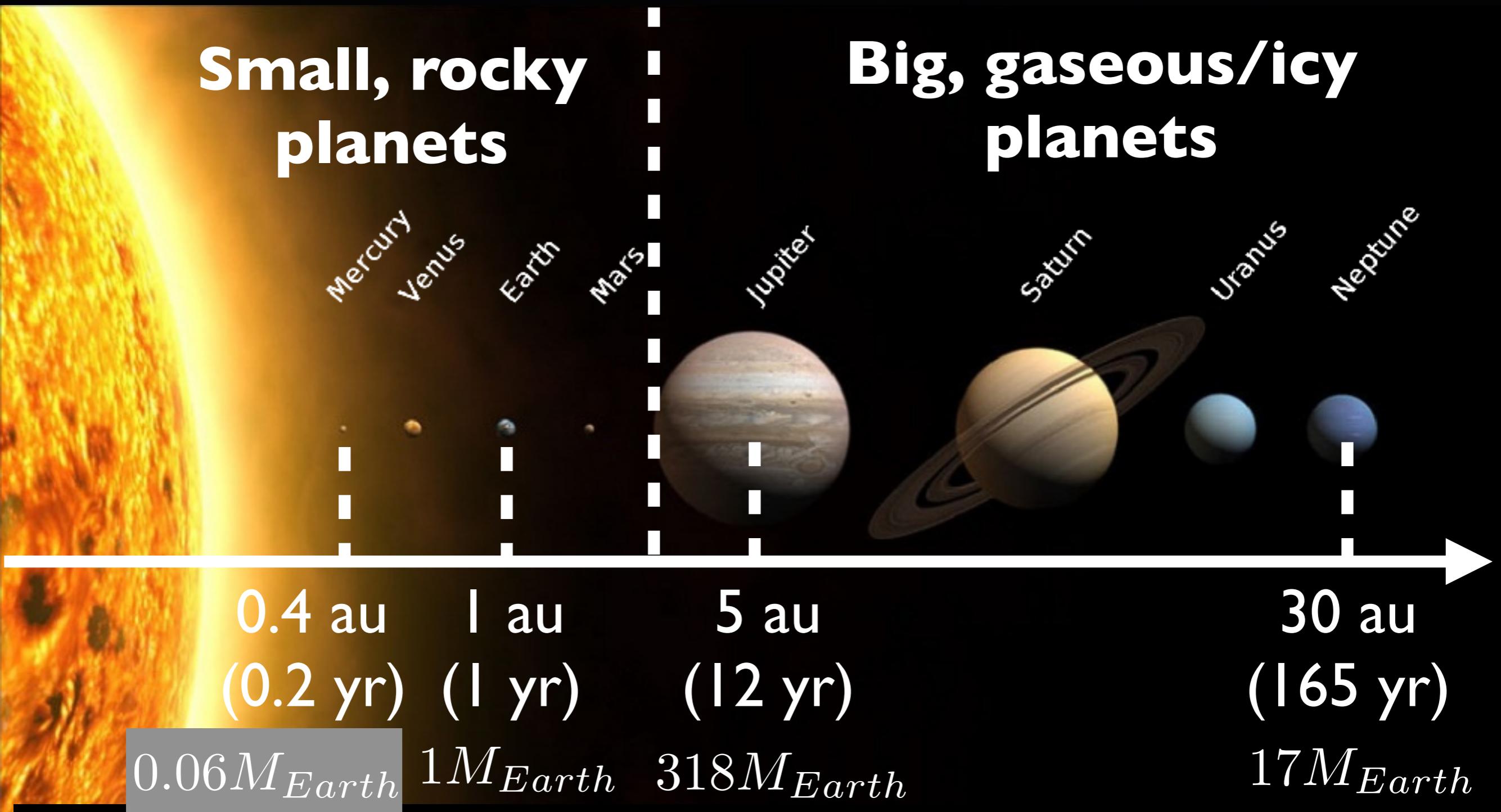
Best Example of Planetary Systems



$$1 \text{ au} = 1.47 \times 10^{13} \text{ cm}$$

$$1M_{Earth} = 5.9 \times 10^{27} \text{ g}$$

Best Example of Planetary Systems



All the planets (except Mercury) are in the circular ($e < 0.1$), coplanar ($i \sim 6$ degree) orbit

“Classical” Picture

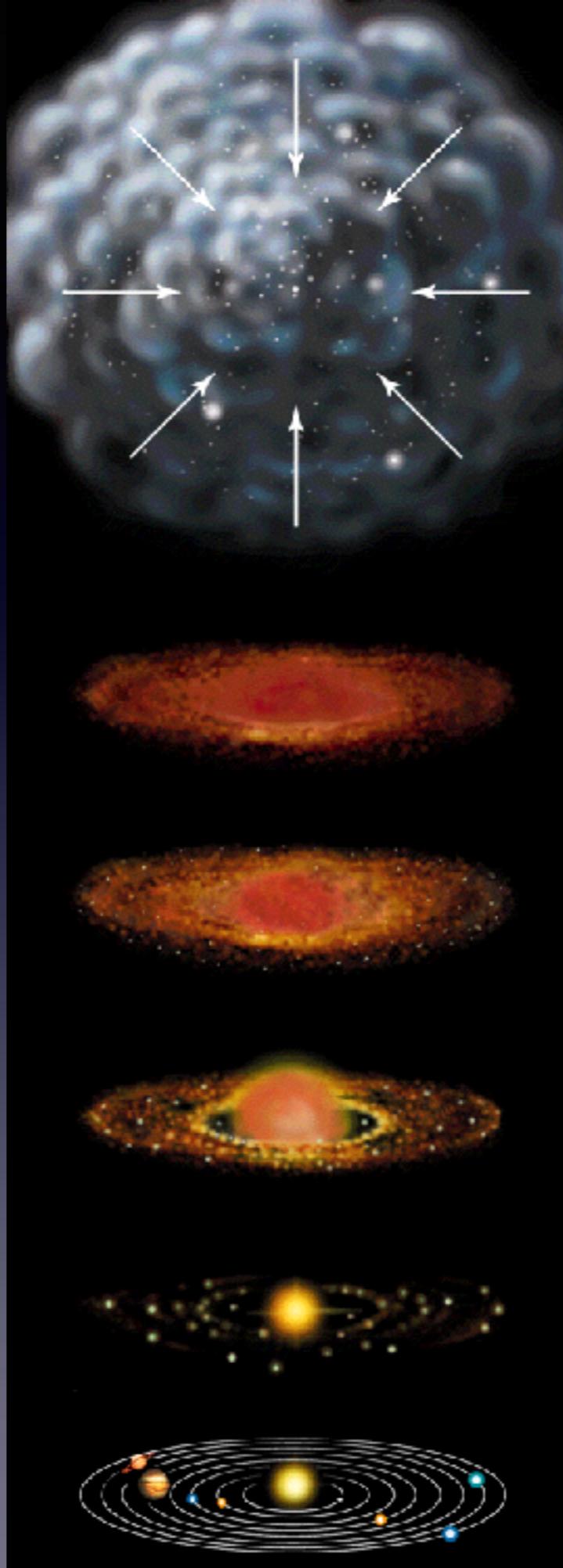
e.g., Hayashi 1981

Natural outcome
of star formation

Minimum-mass
Solar nebula

In-situ formation

Dynamically
inactive



the First Detection of an Extra Solar Planet about 20 years ago

nature

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article

Nature 378, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

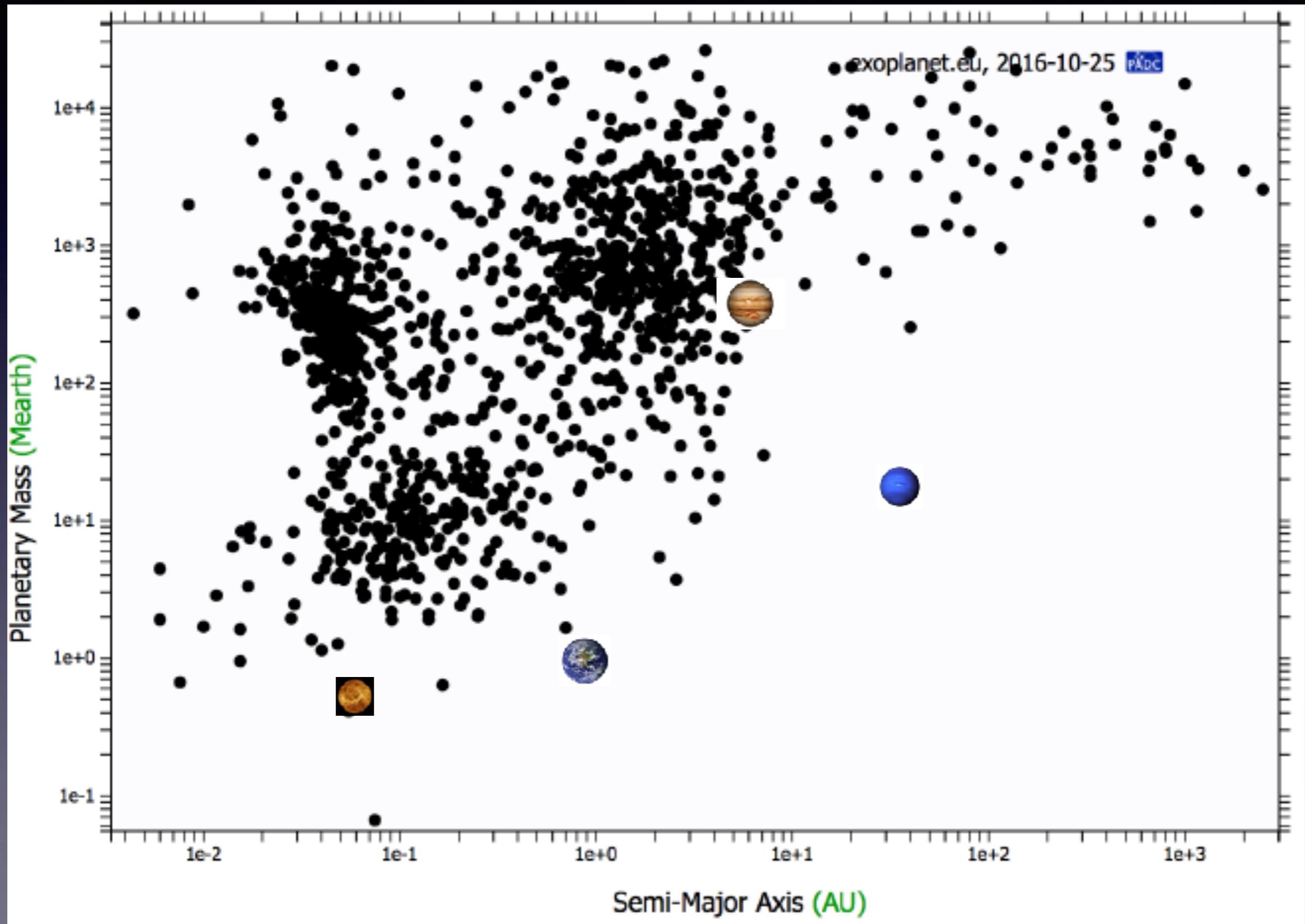
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



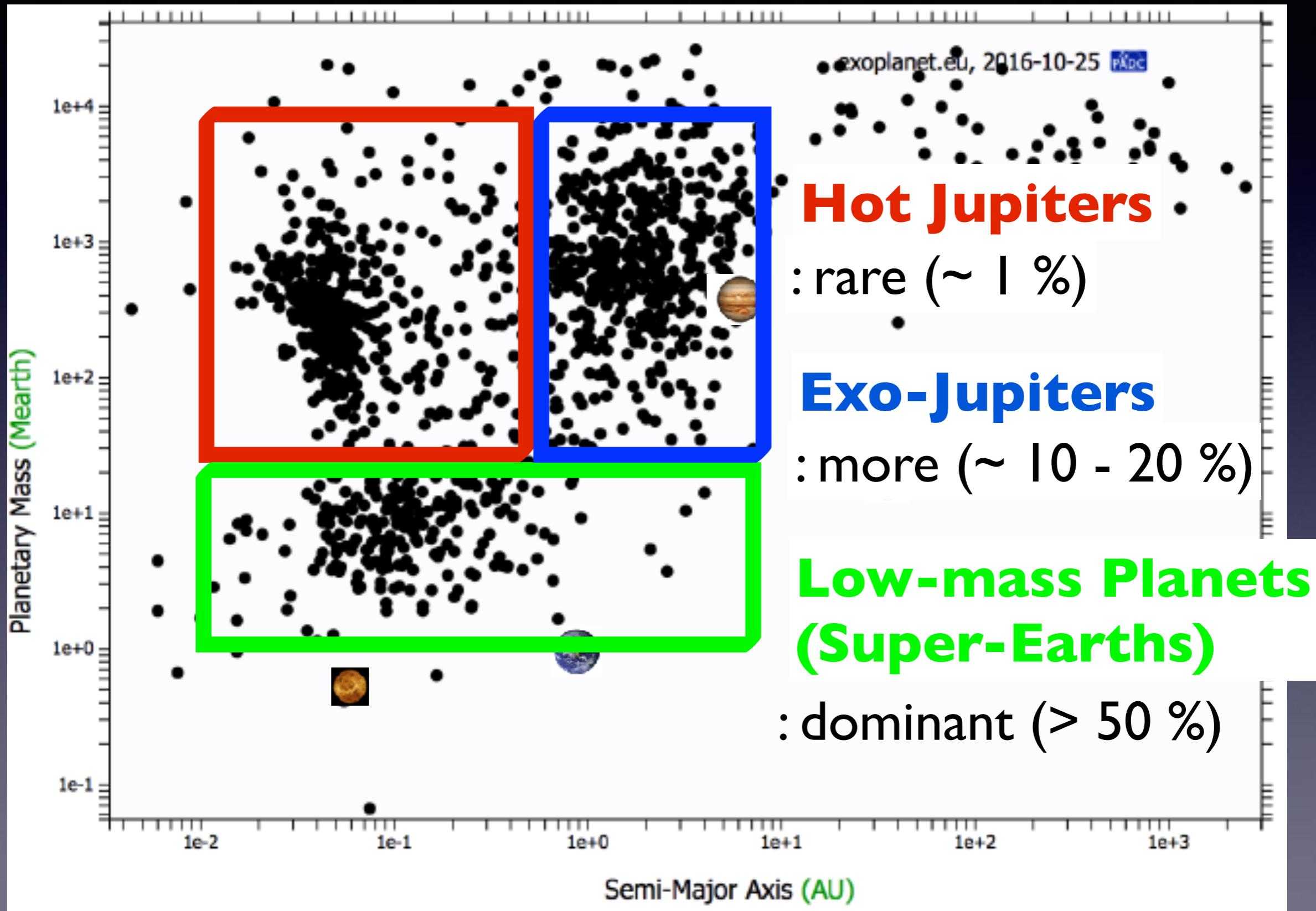
Exoplanetary Populations

e.g., Winn & Fabrycky 2015 for a review



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e.g., Winn & Fabrycky 2015 for a review



“Classical” Picture

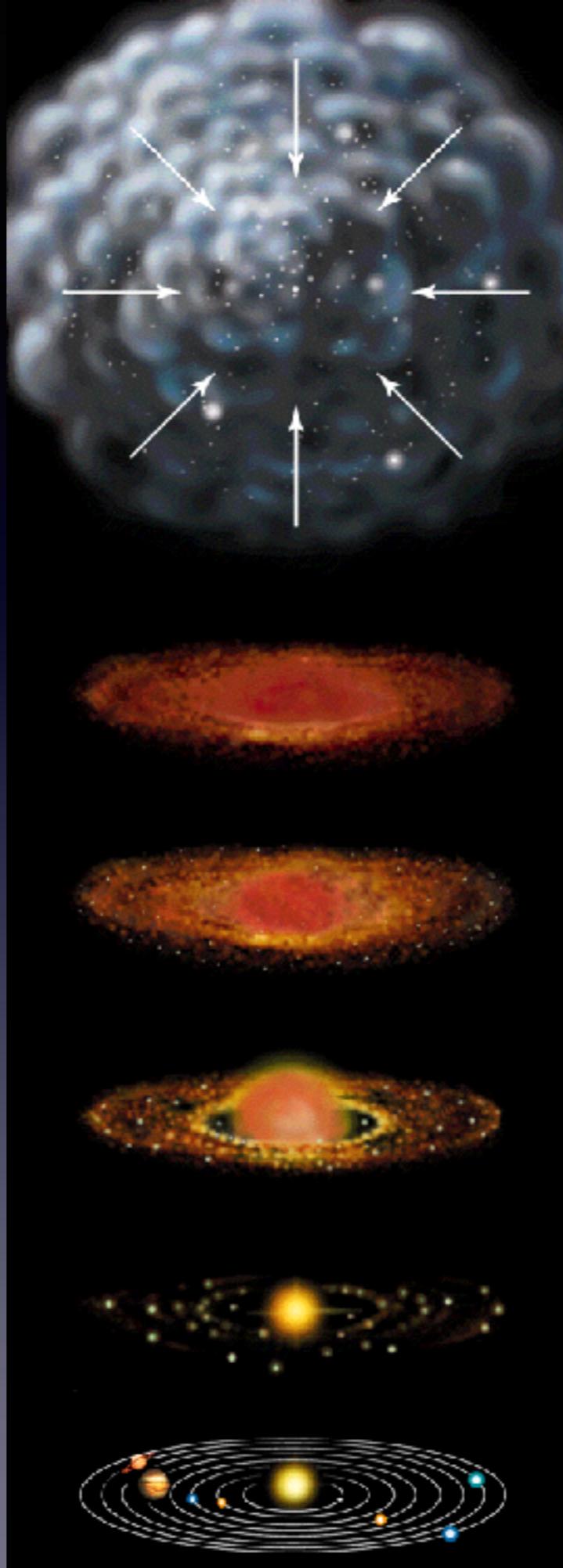
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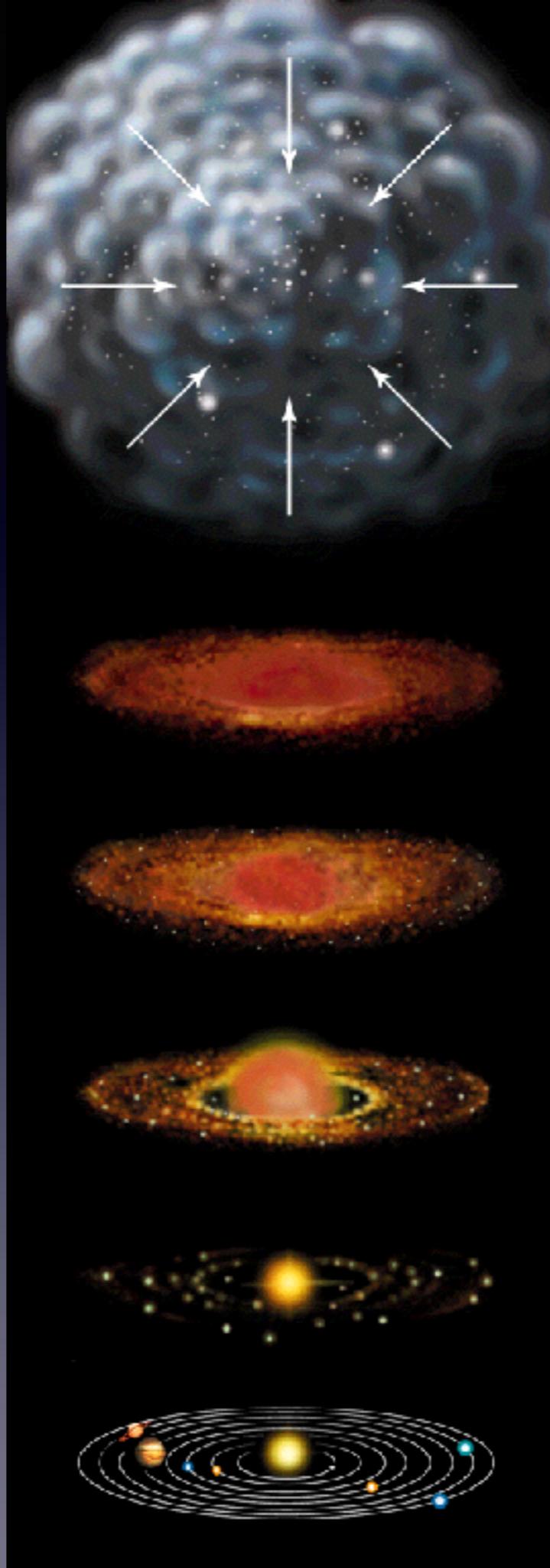
e.g., Hayashi 1981

Natural outcome
of star formation

Minimum-mass
Solar nebula

In-situ formation

Dynamically
inactive



New Picture

Disk model:
Disk evolution,
Spatial distribution
of gas and dust

Planet Formation:
Solar system planets
vs
Exoplanets

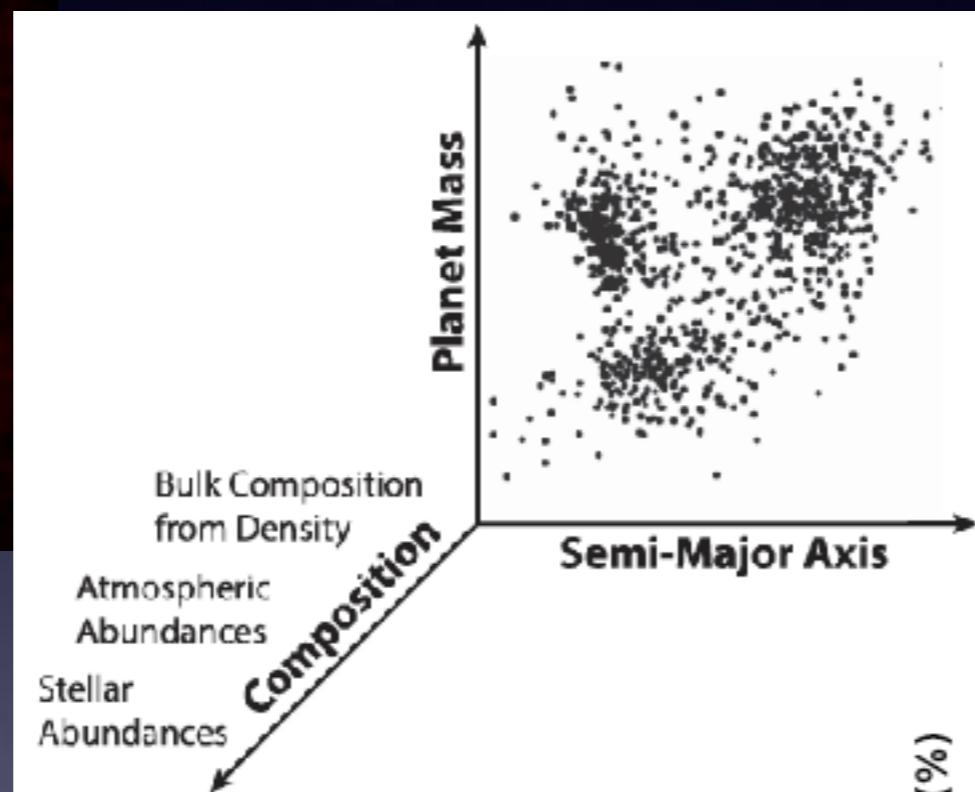
Statistical Approach:
Exoplanet population



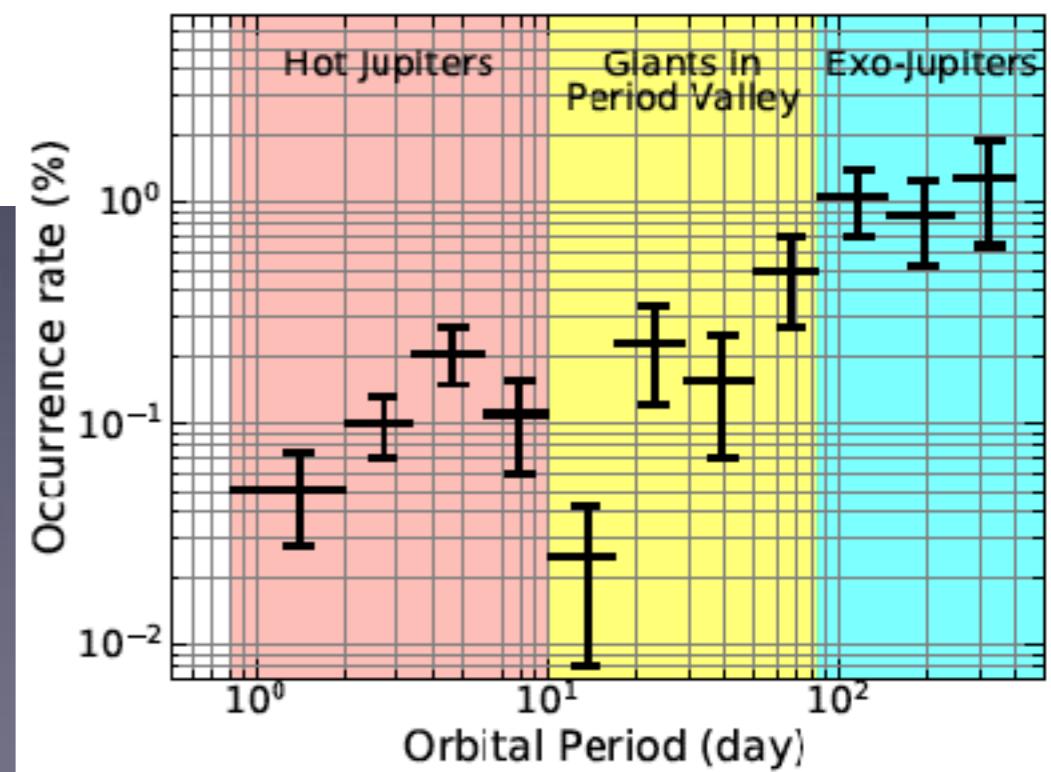
Disk model

New Disk Model

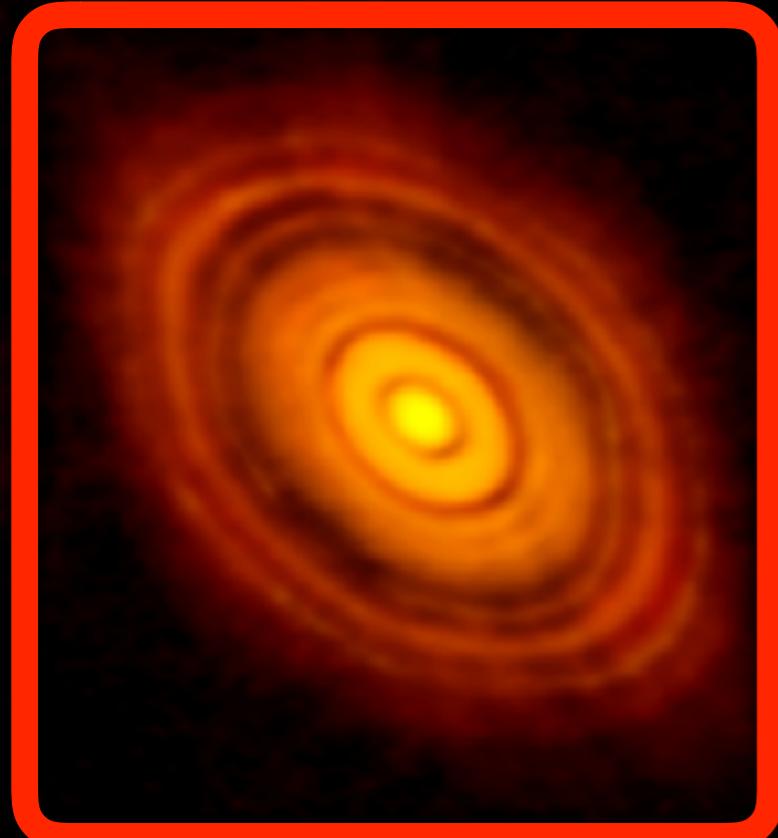
Composition of planets



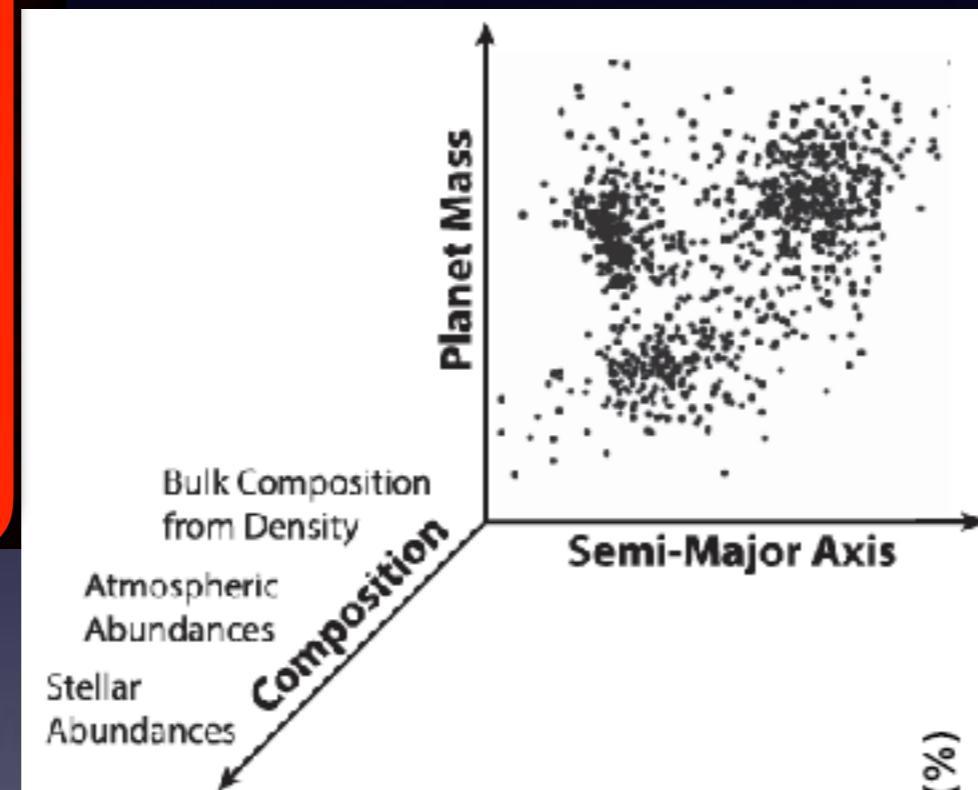
Retrieval approach



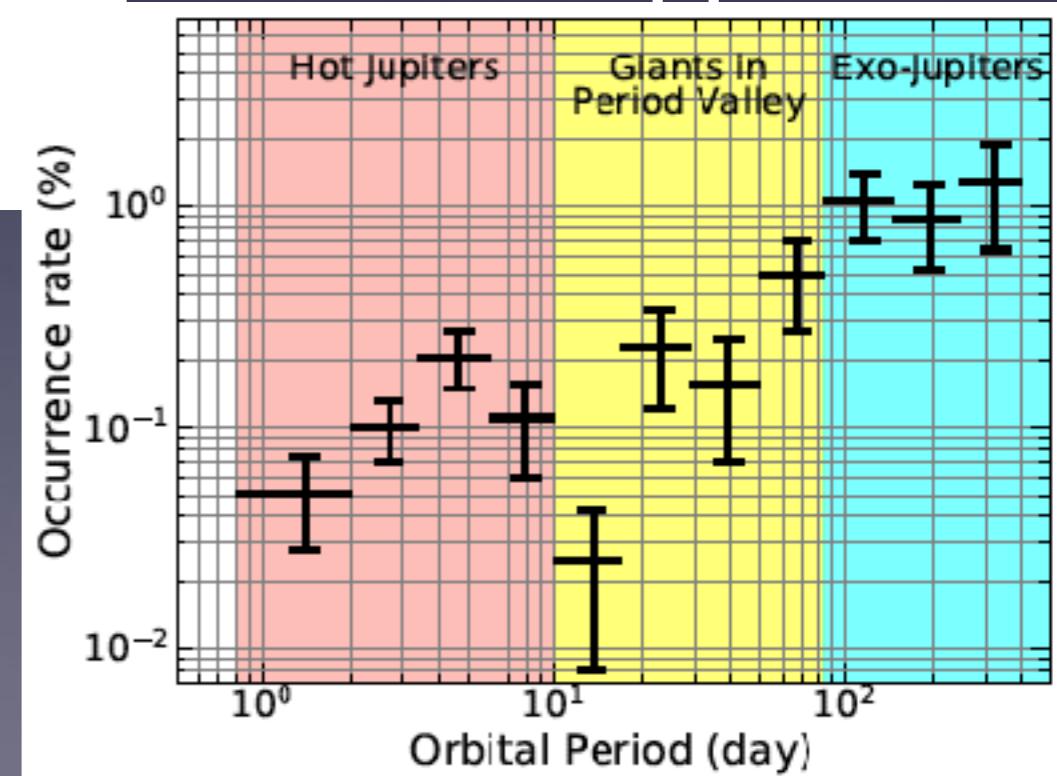
New Disk Model



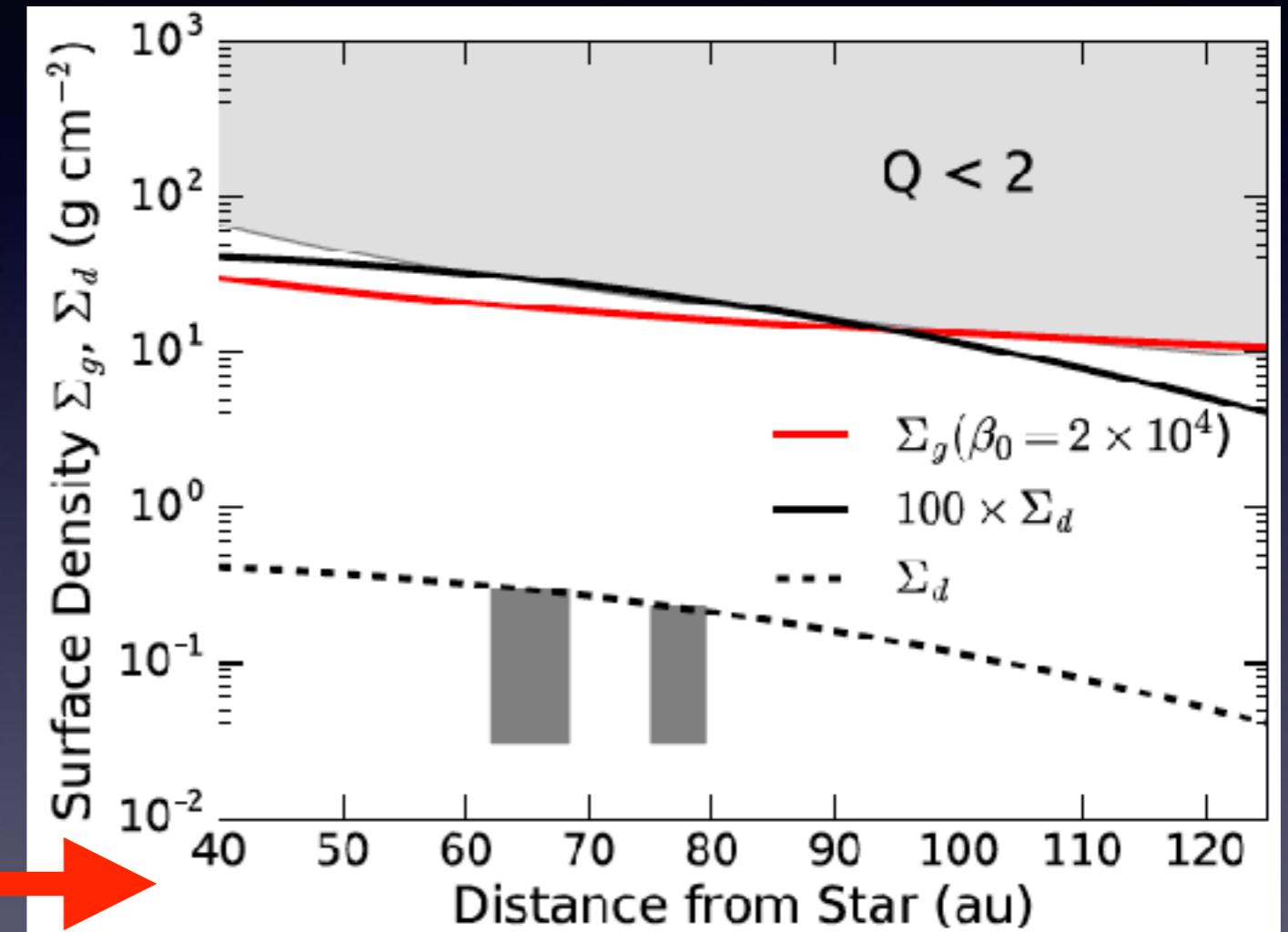
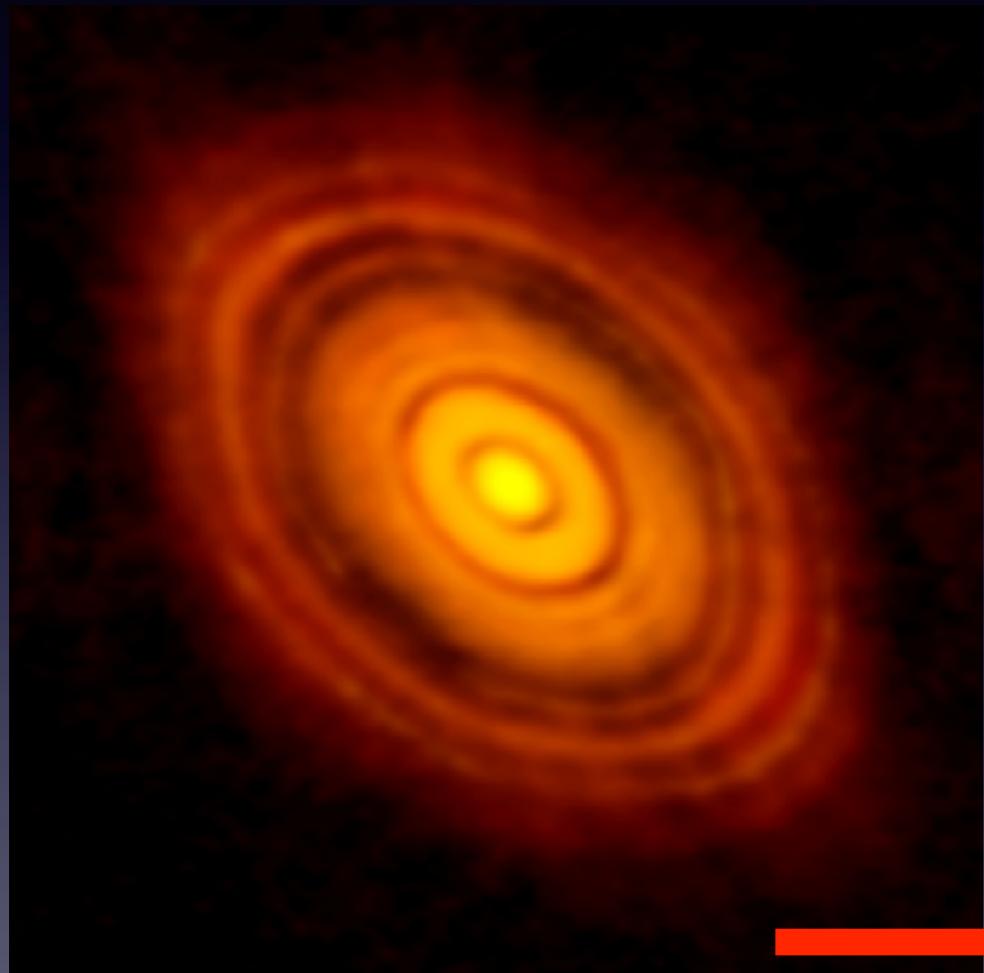
Composition of planets



Retrieval approach



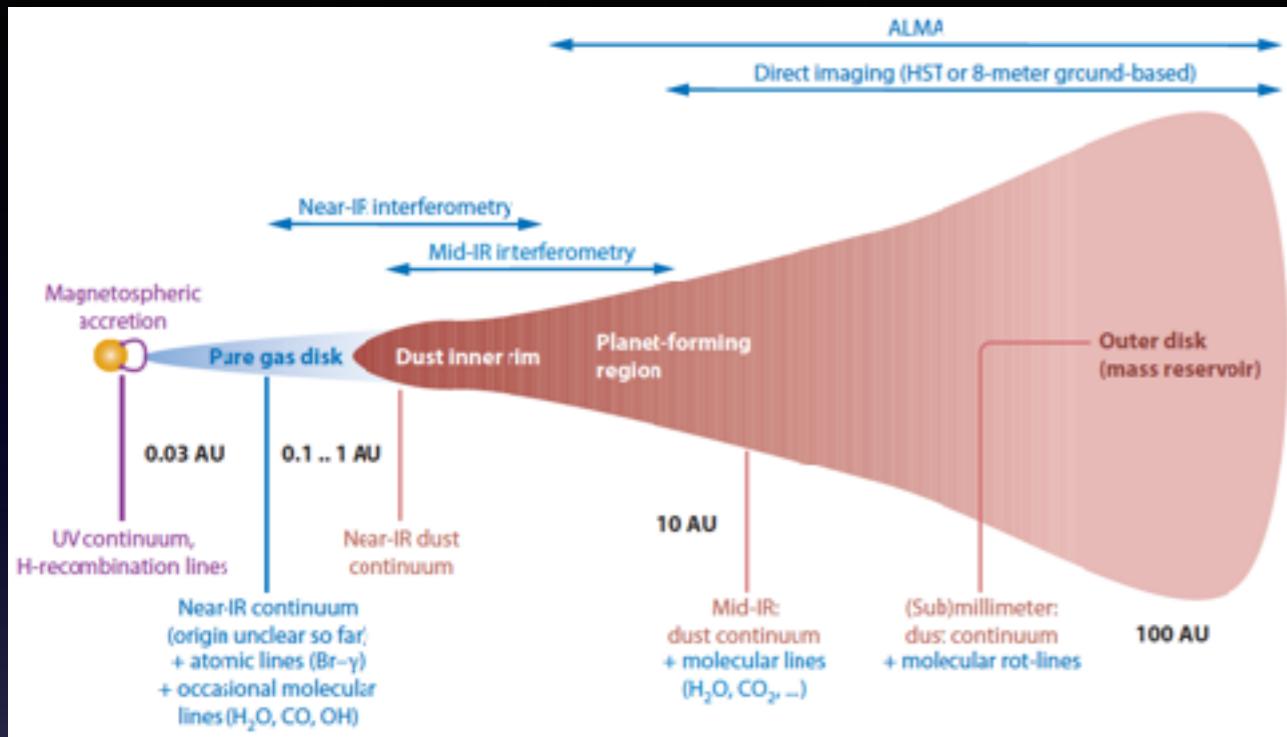
Magnetically Induced Disk Winds and Transport in the HL Tau Disk



in collaboration with
Satoshi Okuzumi (Tokyo Tech), Mario Flock (MPIA), Neal Turner (JPL)

Current Picture of Planet Formation

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_{\odot}$$

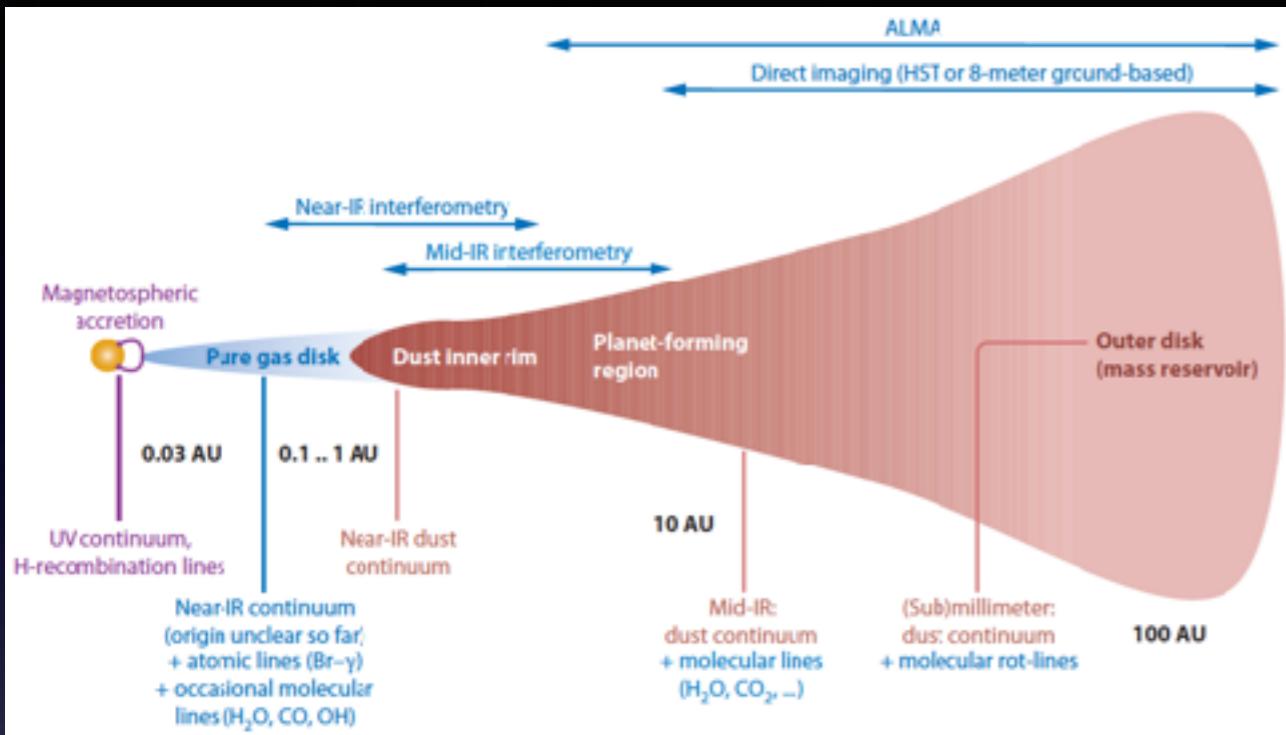
(: $\sim 99\%$ of gas and $\sim 1\%$ of dust)

$$\tau_{disk} \sim 10^6 - 10^7 \text{ yr}$$

Disks are turbulent
possibly by magnetic fields

Current Picture of Planet Formation

e.g., Hayashi 1981



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At 1 au, $n \sim 10^{14} \text{ cm}^{-3}$

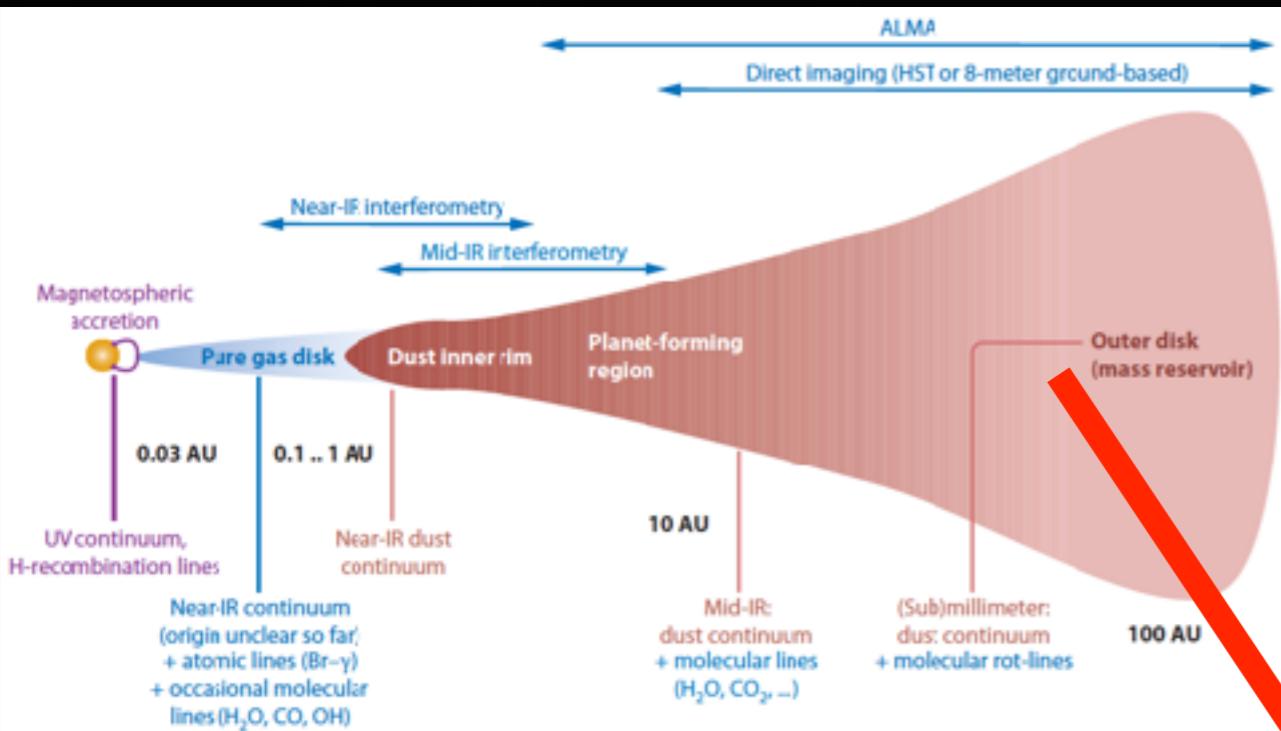
$T \sim 300K$

cf) the atmosphere of the Earth,

At 1 bar, $n \sim 10^{19} \text{ cm}^{-3}$

Current Picture of Planet Formation

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_{\odot}$$

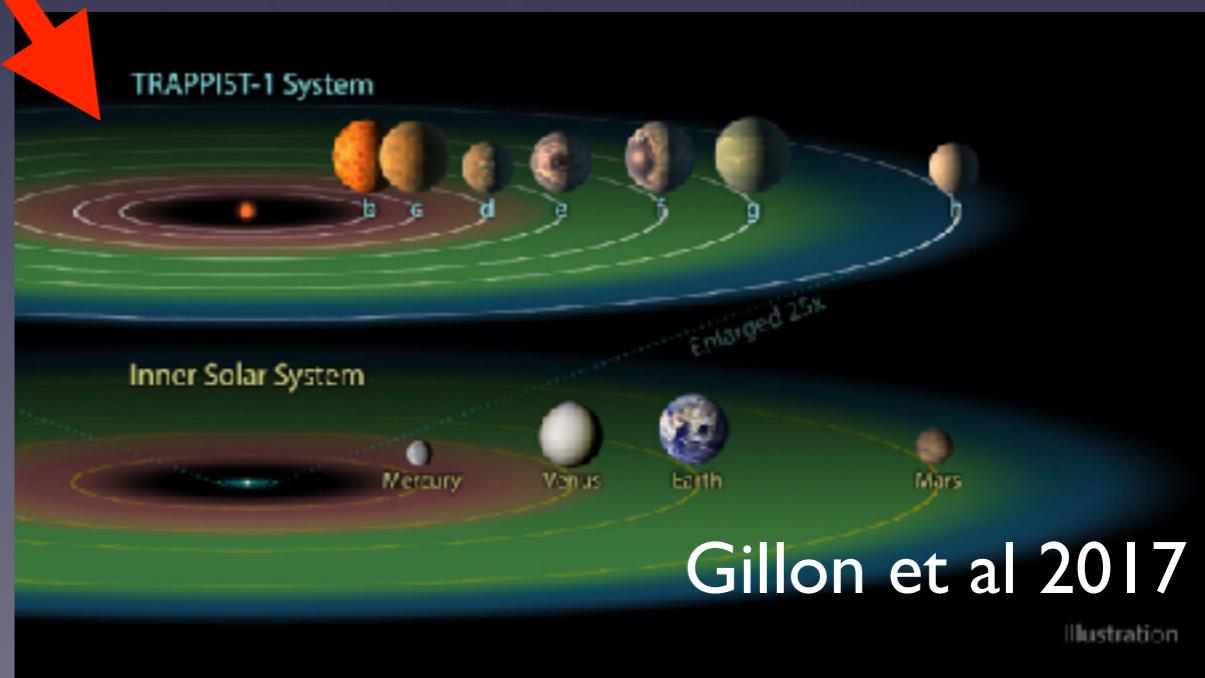
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Disks are turbulent
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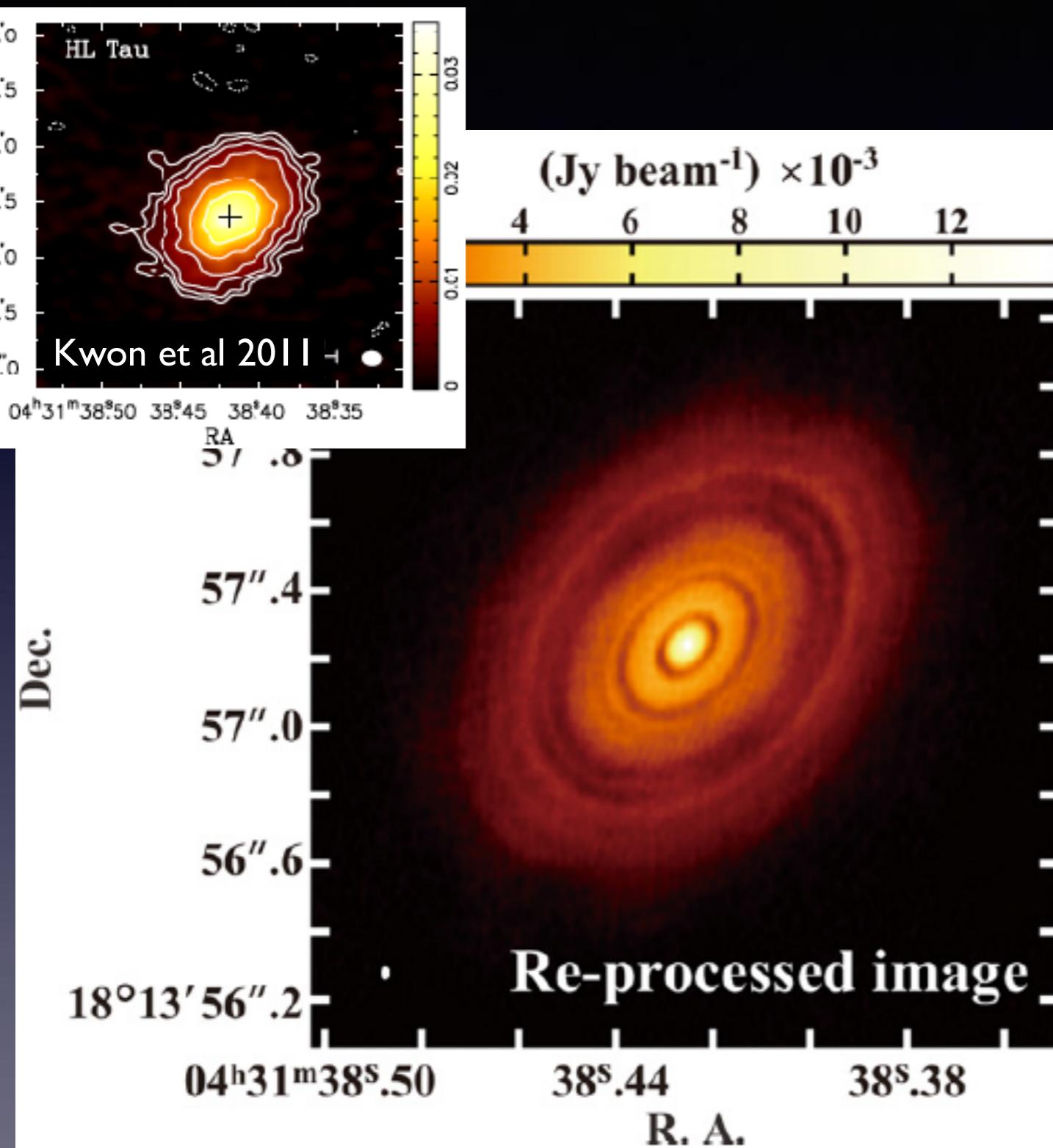
At 1 au, $n \sim 10^{14} \text{ cm}^{-3}$
 $T \sim 300K$

cf) the atmosphere of the Earth,
At 1 bar, $n \sim 10^{19} \text{ cm}^{-3}$



Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015,
also see Akiyama YH et al 2016



HL Tau : a Class I/II YSO
: ~140 pc (< 1 Myrs)

Nearly concentric
multiple gaps in
the dust thermal emission

Potential signature of
planet formation

The origin of observed gaps is not identified yet!!

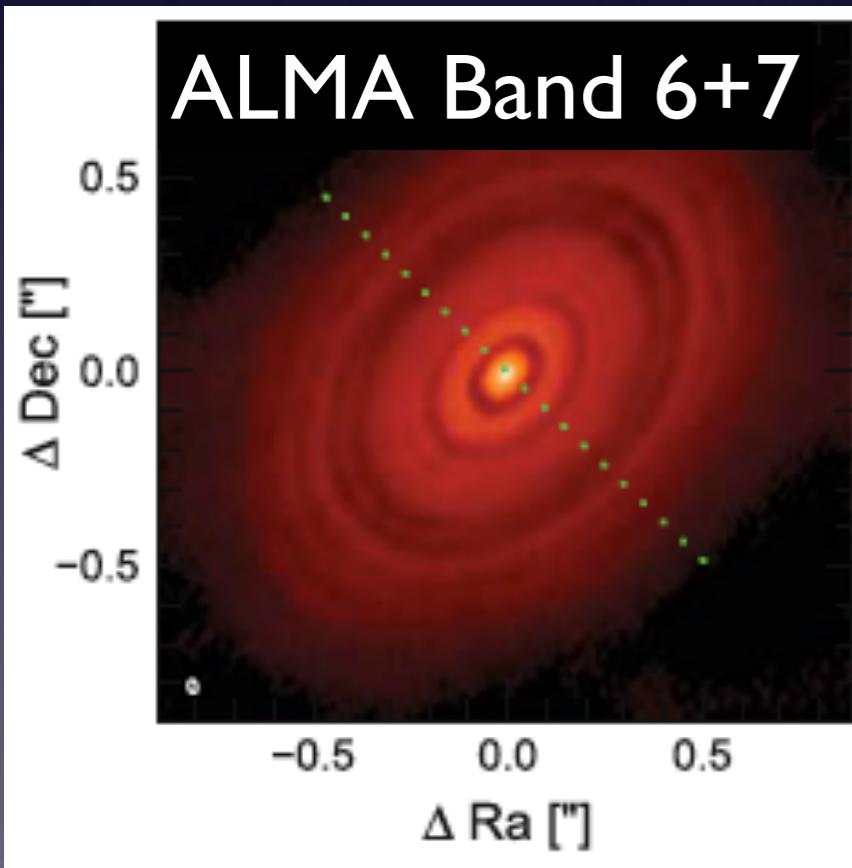
Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\text{GL}} \simeq 10^{-2} - 10^{-1}$

=> can be explained by MRI and MHD turbulence



ALMA Partnership et al 2015
also see Akiyama et al 2016

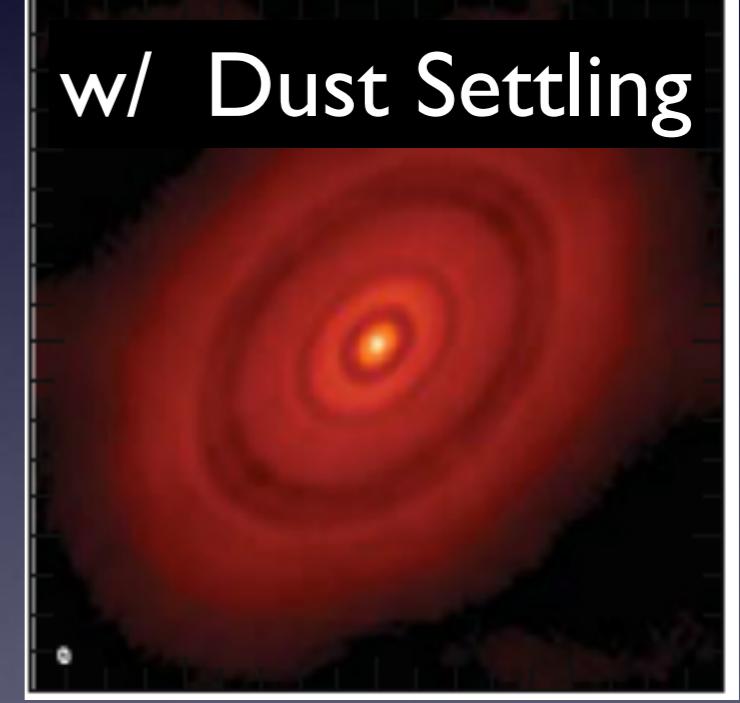
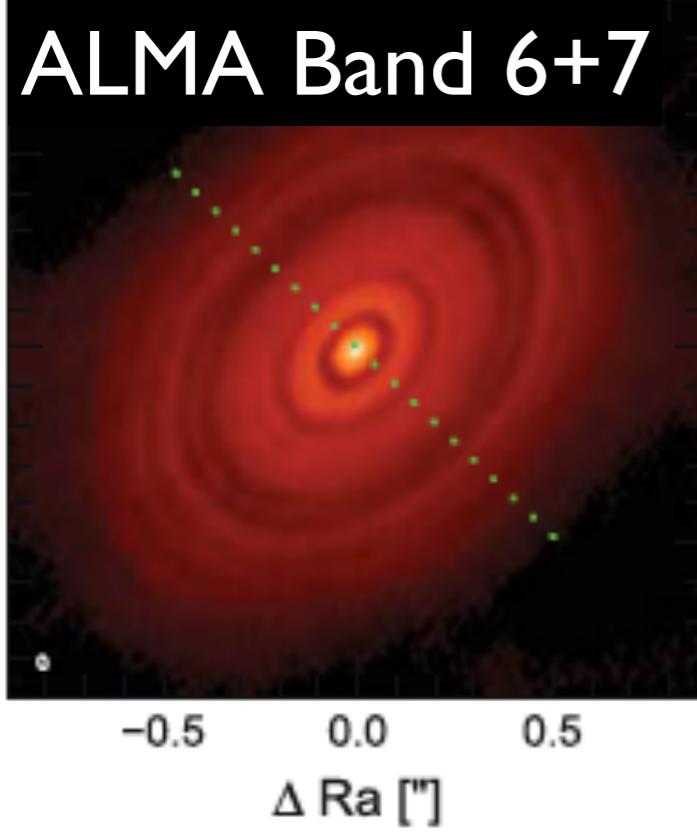
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Hayashi et al 1993, Beck et al 2010

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Pinte et al 2016

Vertical dust height: $\sim 1 \text{ au}$ at $r = 100 \text{ au}$
Local diffusion coefficient: $\alpha_{\text{LC}} \sim 10^{-4}$

Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\text{GL}} \simeq 10^{-2} - 10^{-1}$

I) How does the HL Tau disk
keep a high disk accretion rate
without exciting local turbulence??

2) Why can the HL Tau disk avoid GI??

$\Delta \text{Ra} ["]$

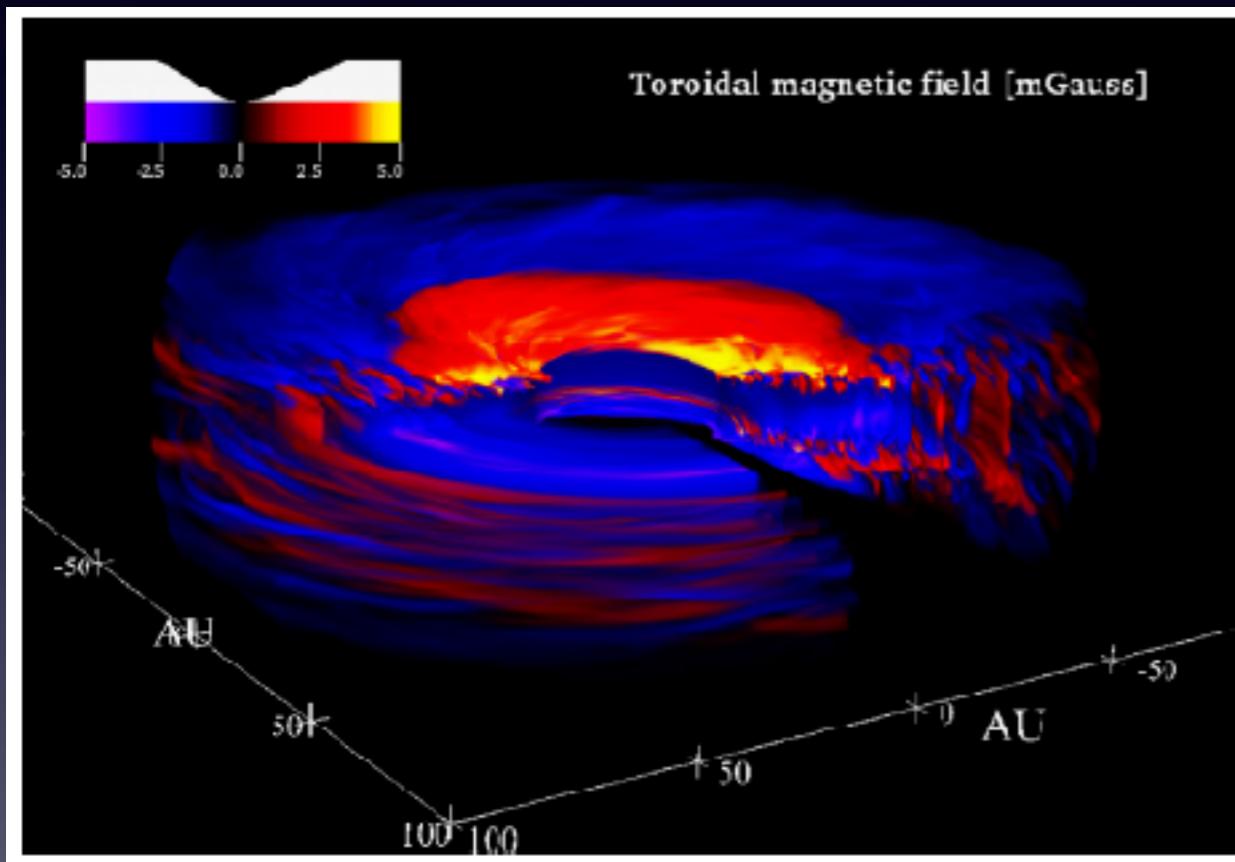
Pinte et al 2016

Vertical dust height: $\sim 1 \text{ au}$ at $r = 100 \text{ au}$
Local diffusion coefficient: $\alpha_{\text{LC}} \sim 10^{-4}$

Magnetically Driven Disk Accretion

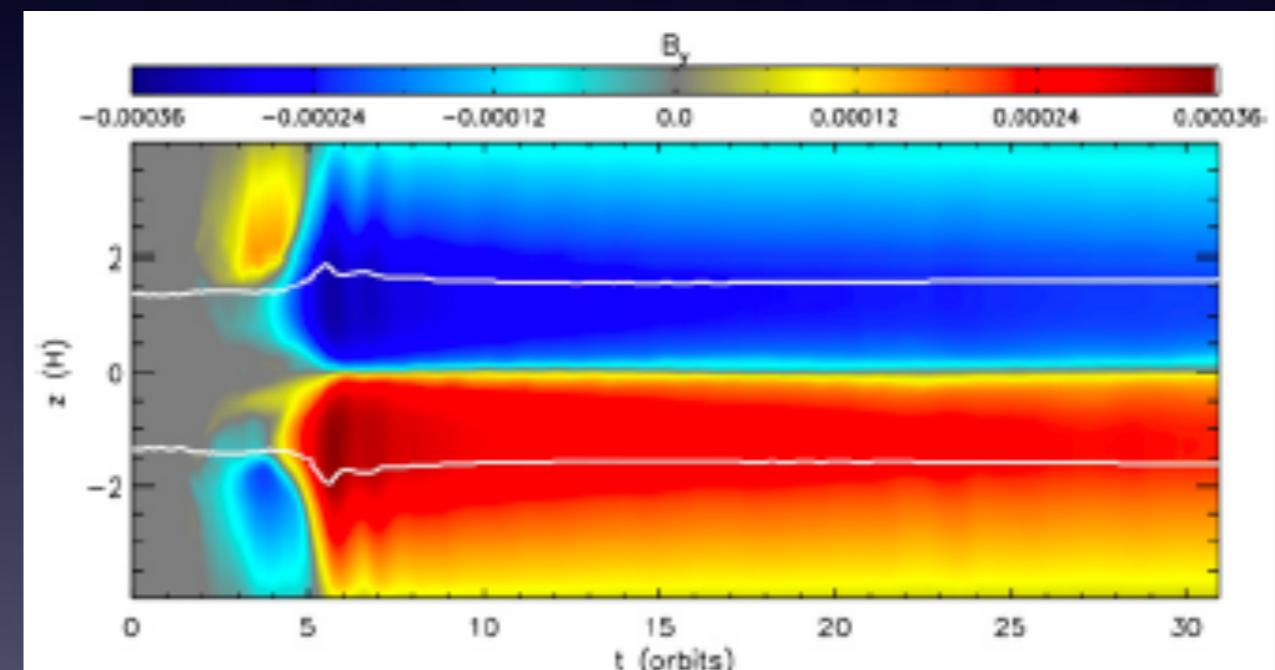
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence

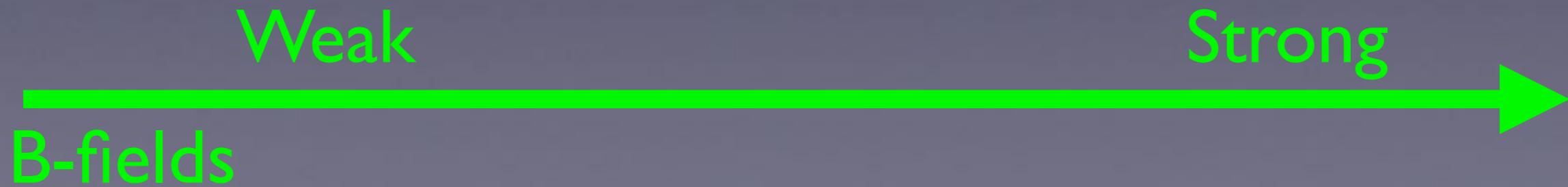


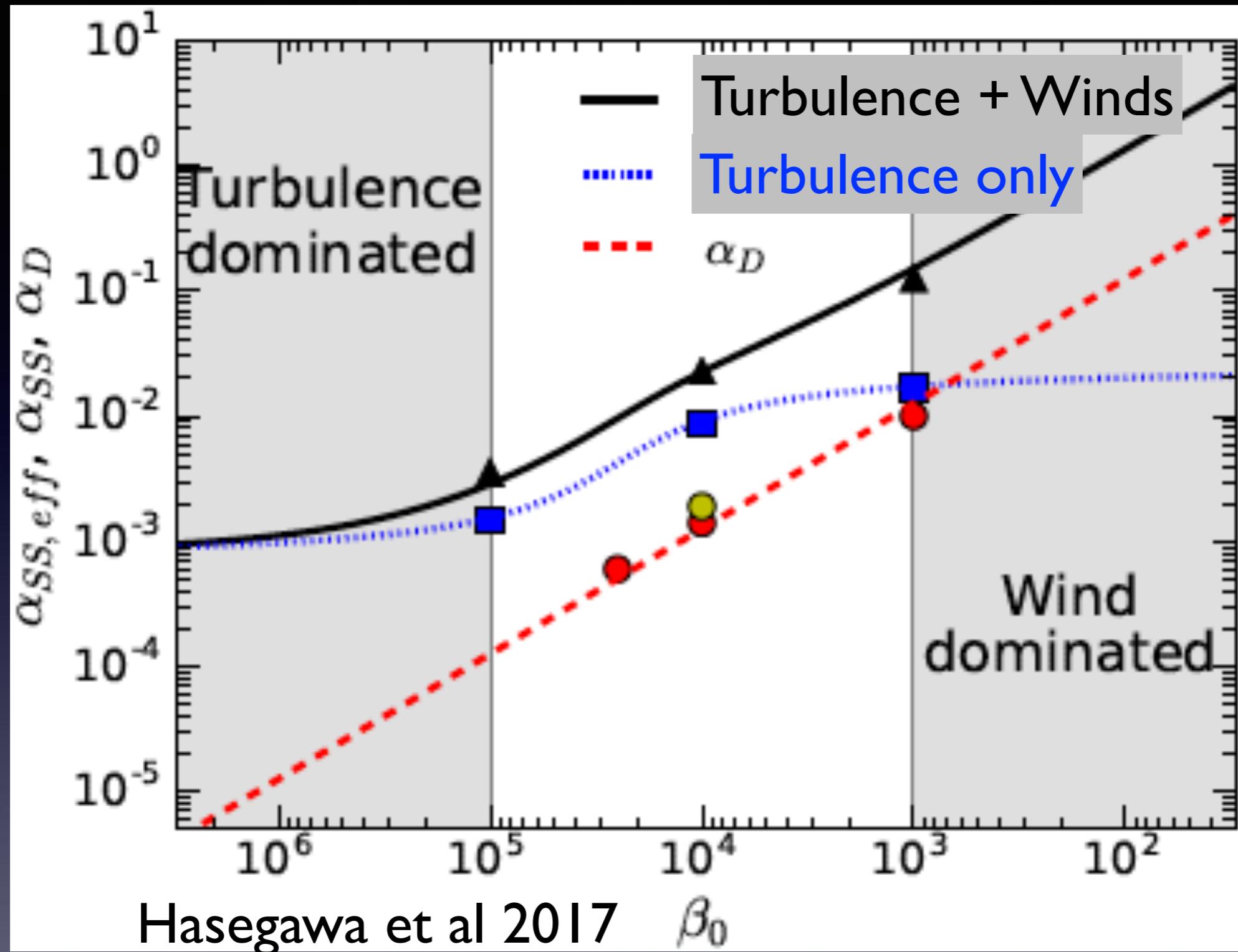
Flock et al 2015

Magnetically Induced Disk Winds



Simon et al 2013





α_D : vertical mixing of dust

Weak

B-fields

β_0 : the plasma beta

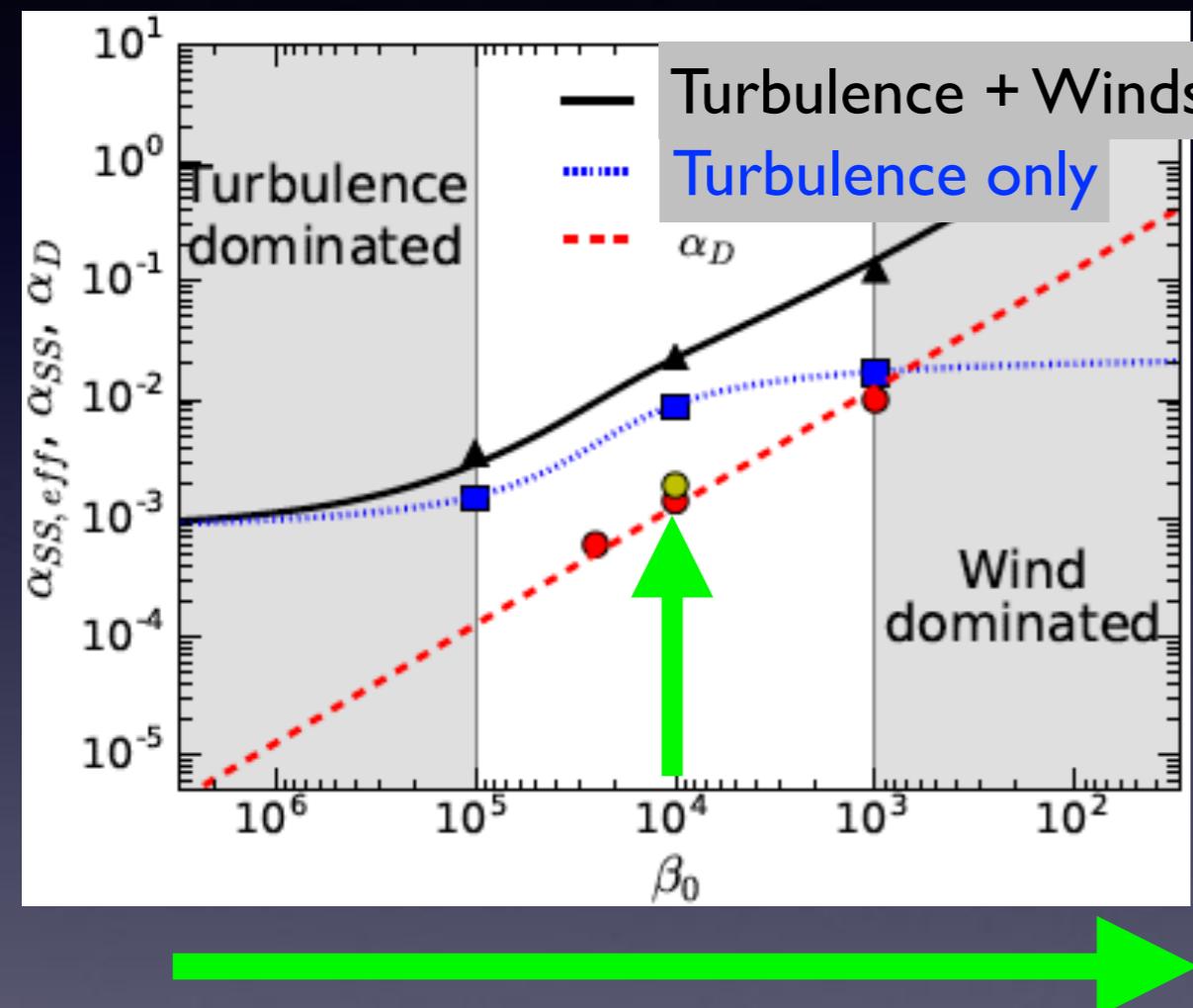
Strong

Simulation results from Simon et al 2013, Zhu et al 2015 are used

Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

I. Gas surface density



2. Dust height

B-fields

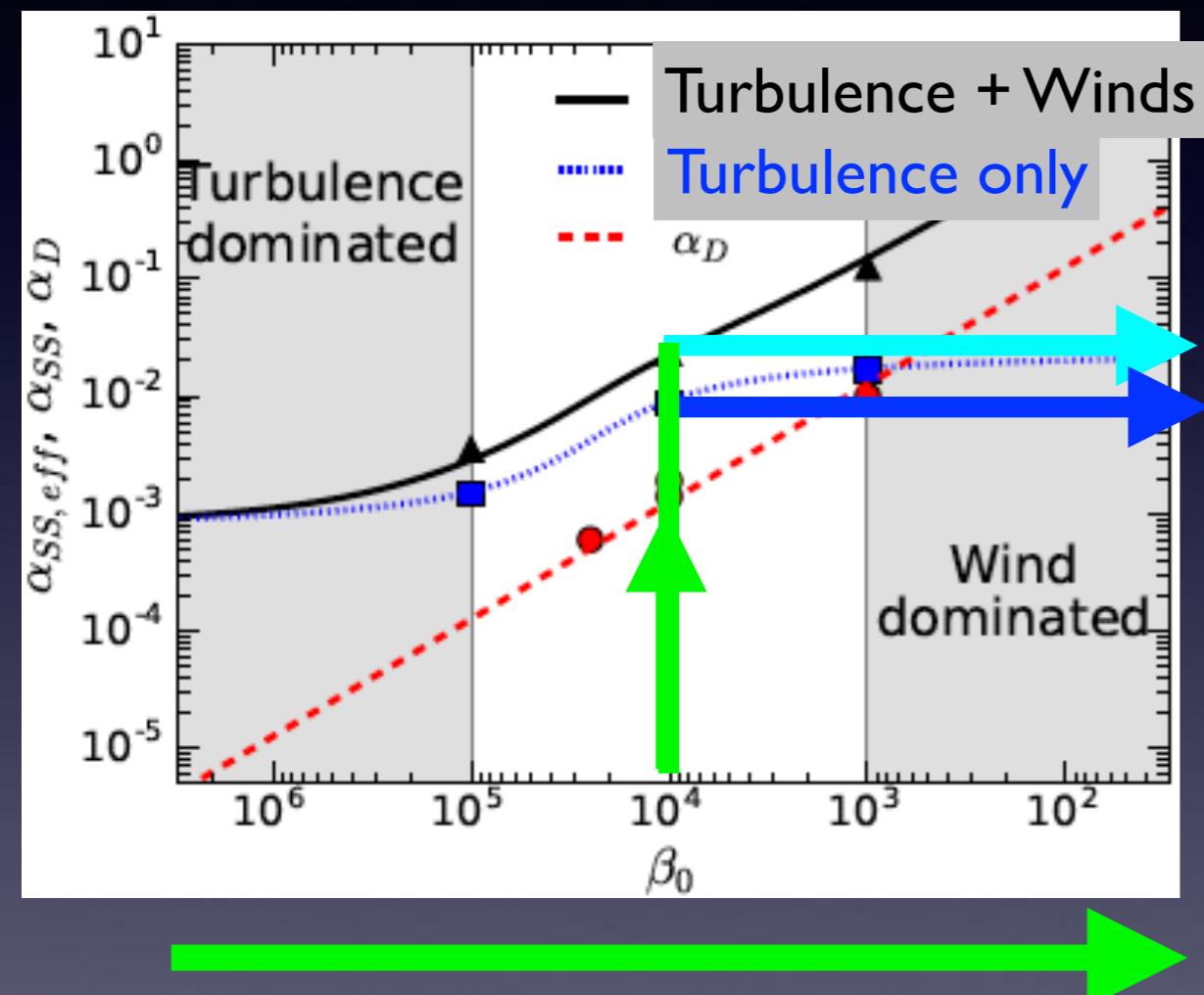
Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

1. Gas surface density

$$\Sigma_g = \frac{\dot{M} \Omega}{3\pi \alpha_{GL} c_s^2}$$

2. Dust height



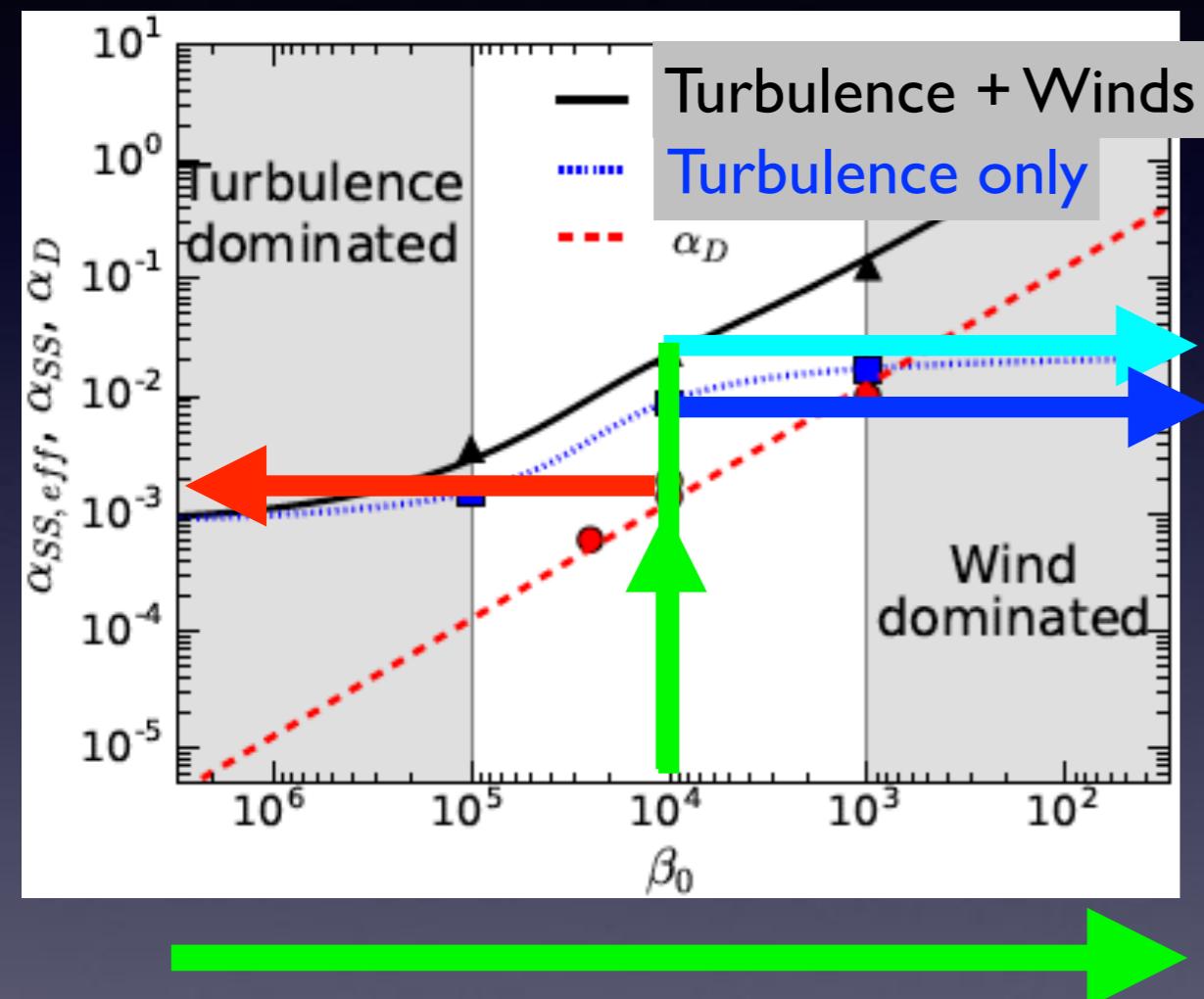
B-fields

Given that

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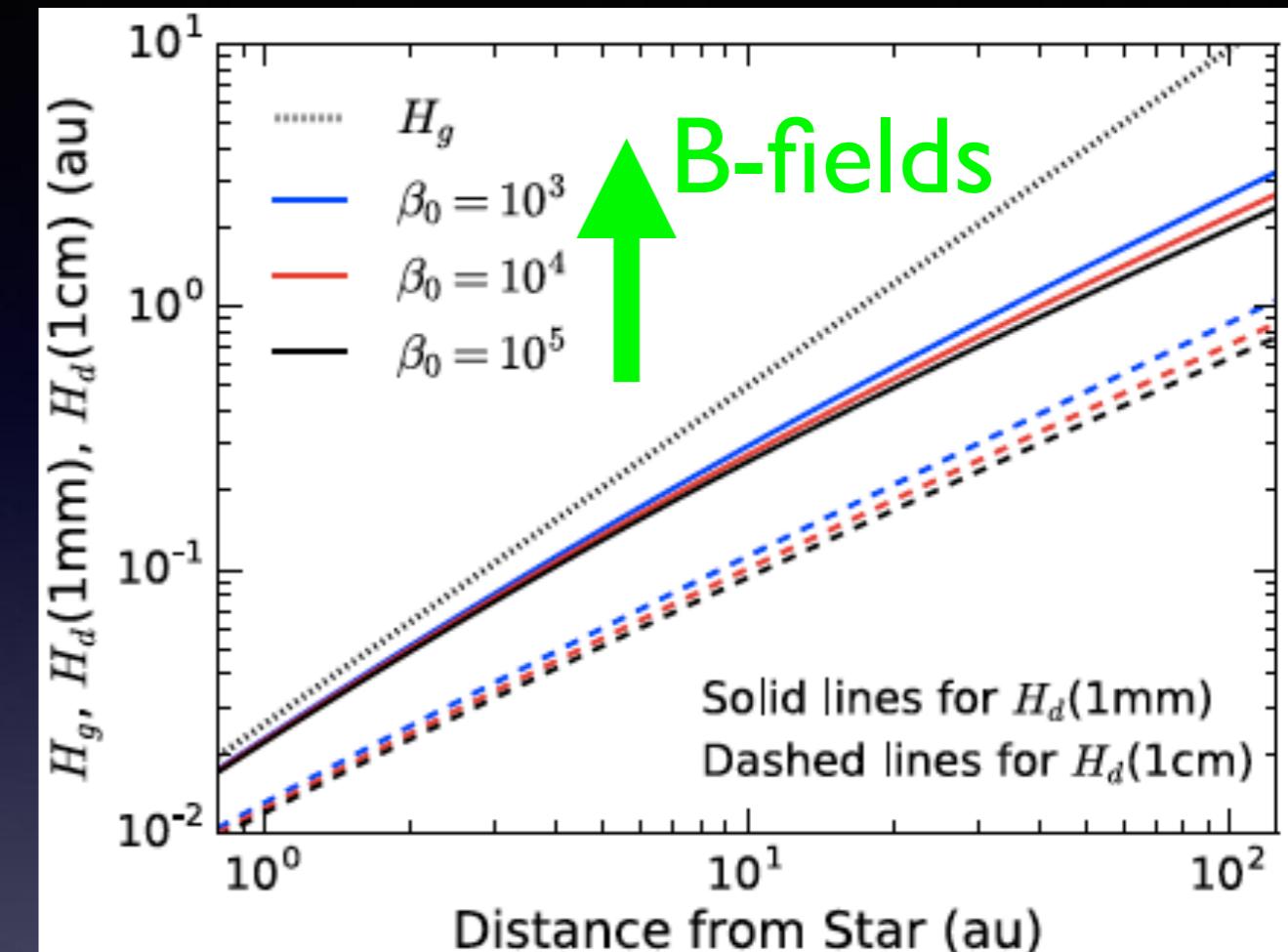
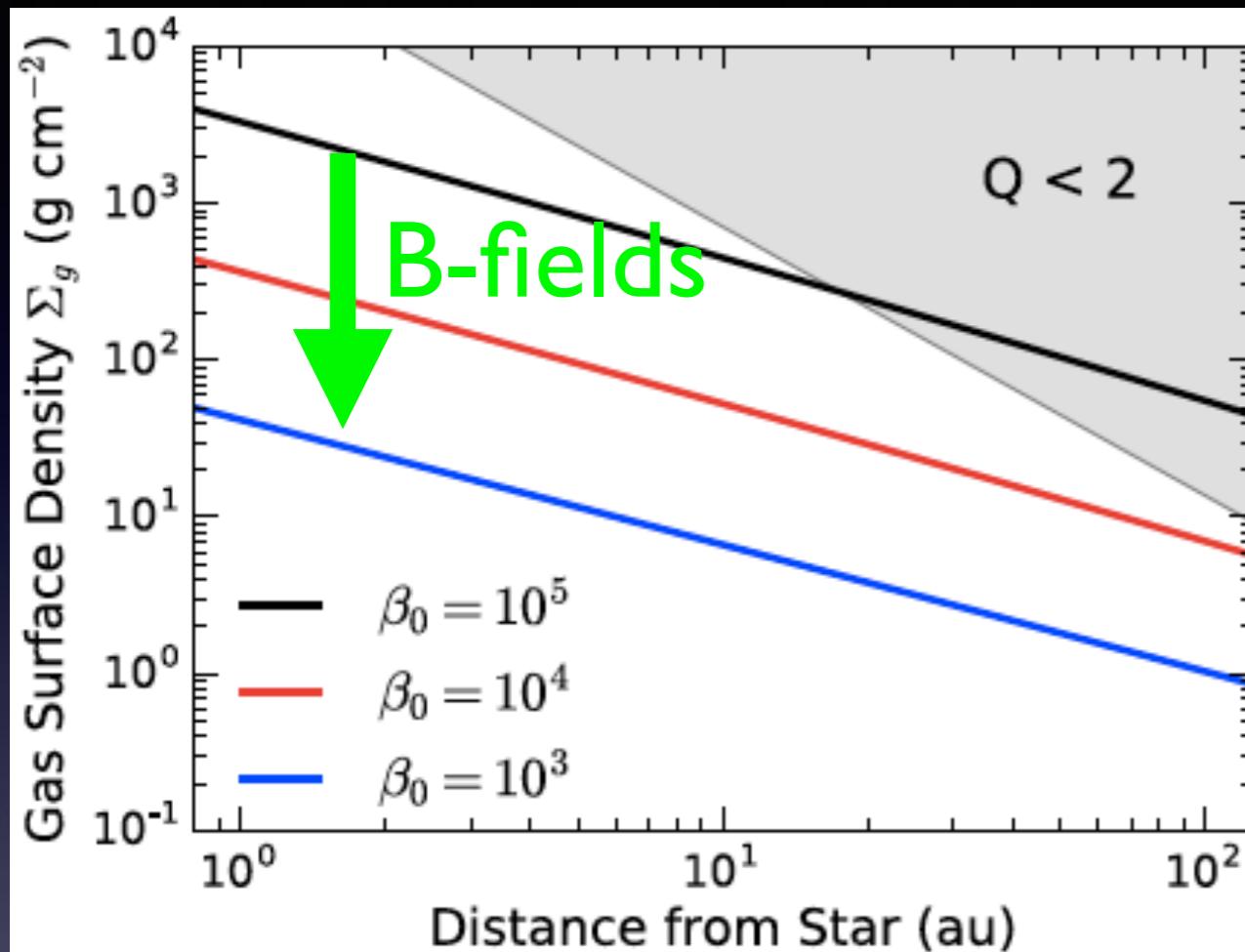
B-fields

2. Dust height

$$H_d = \left(1 + \frac{St}{\alpha_D} \right)^{-1/2} H_g$$

$$St \propto \frac{a}{\Sigma_g}$$

Ex) Resulting Disk Structures with Disk Winds

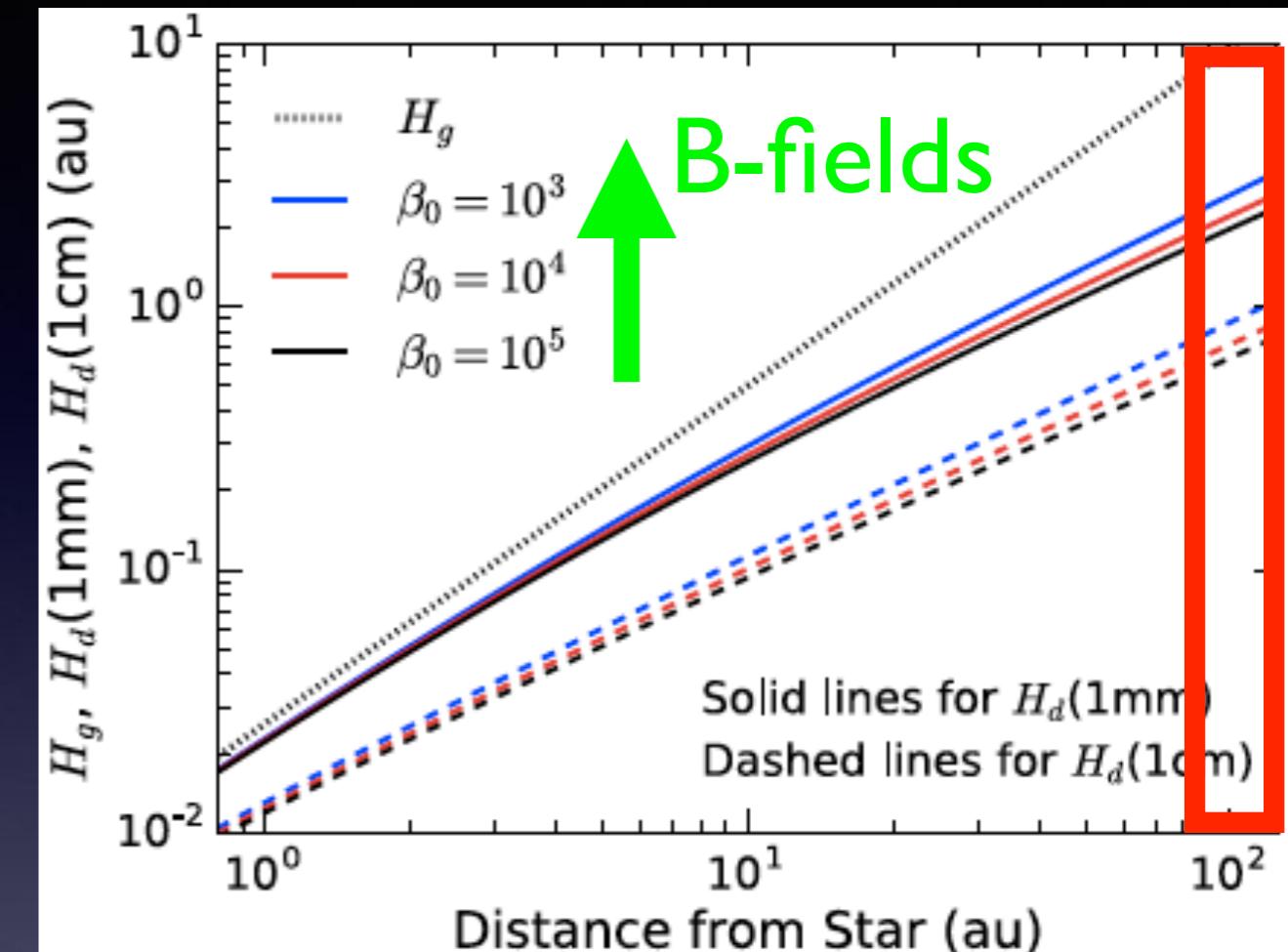
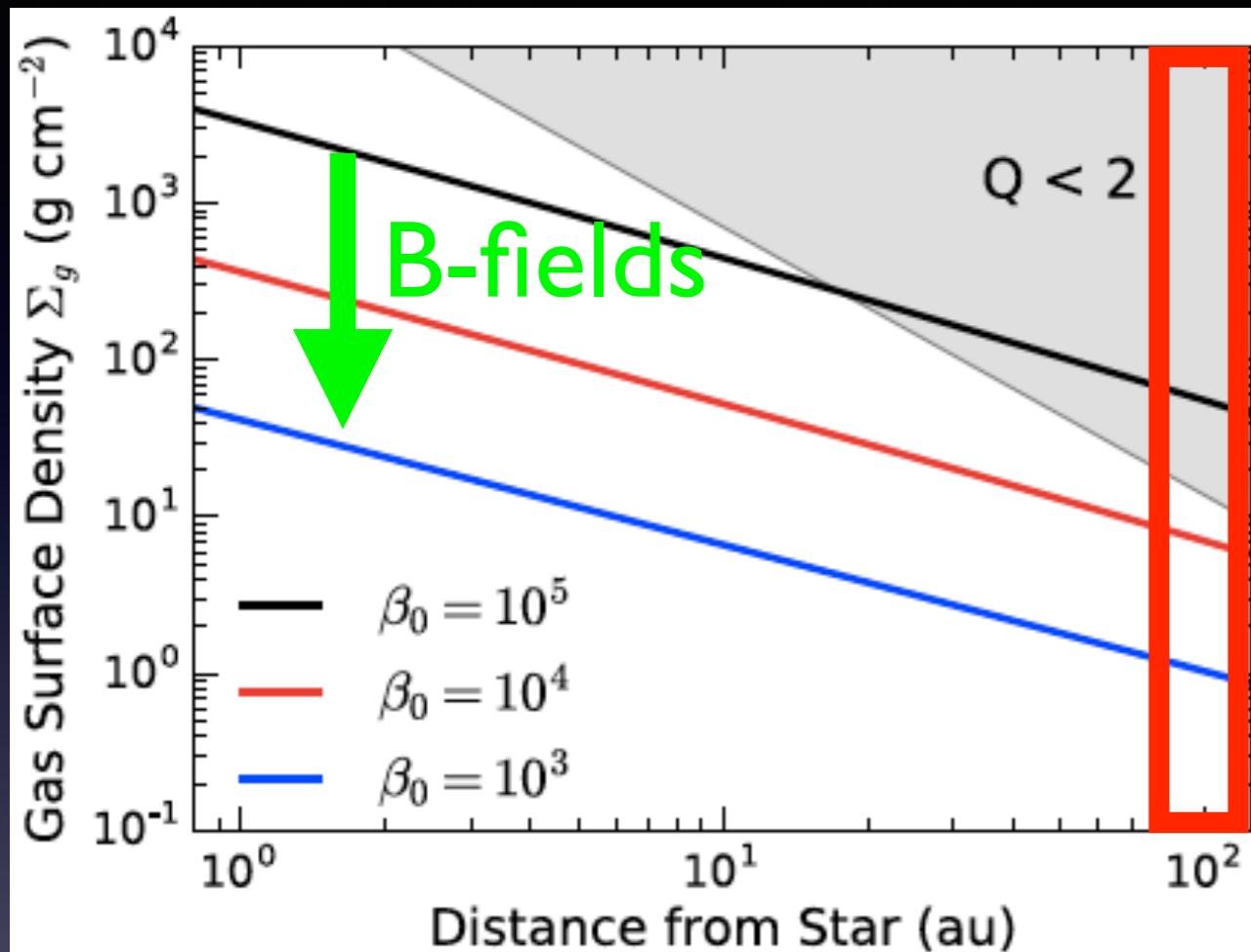


As B-fields are stronger,
surface density decreases
due to disk winds

Dust scale heights are
independent of B-fields

Results are obtained for given values of disk accretion rate, disk temperature

Ex) Resulting Disk Structures with Disk Winds



Focus on the HL Tau disk

Inversely solve the problem

I. Find β_0 with which
 Σ_g marginally avoids GI

II. Find β_0 with which
the dust size satisfies
 $H_d = 1$ au

Results at $r = 100$ au

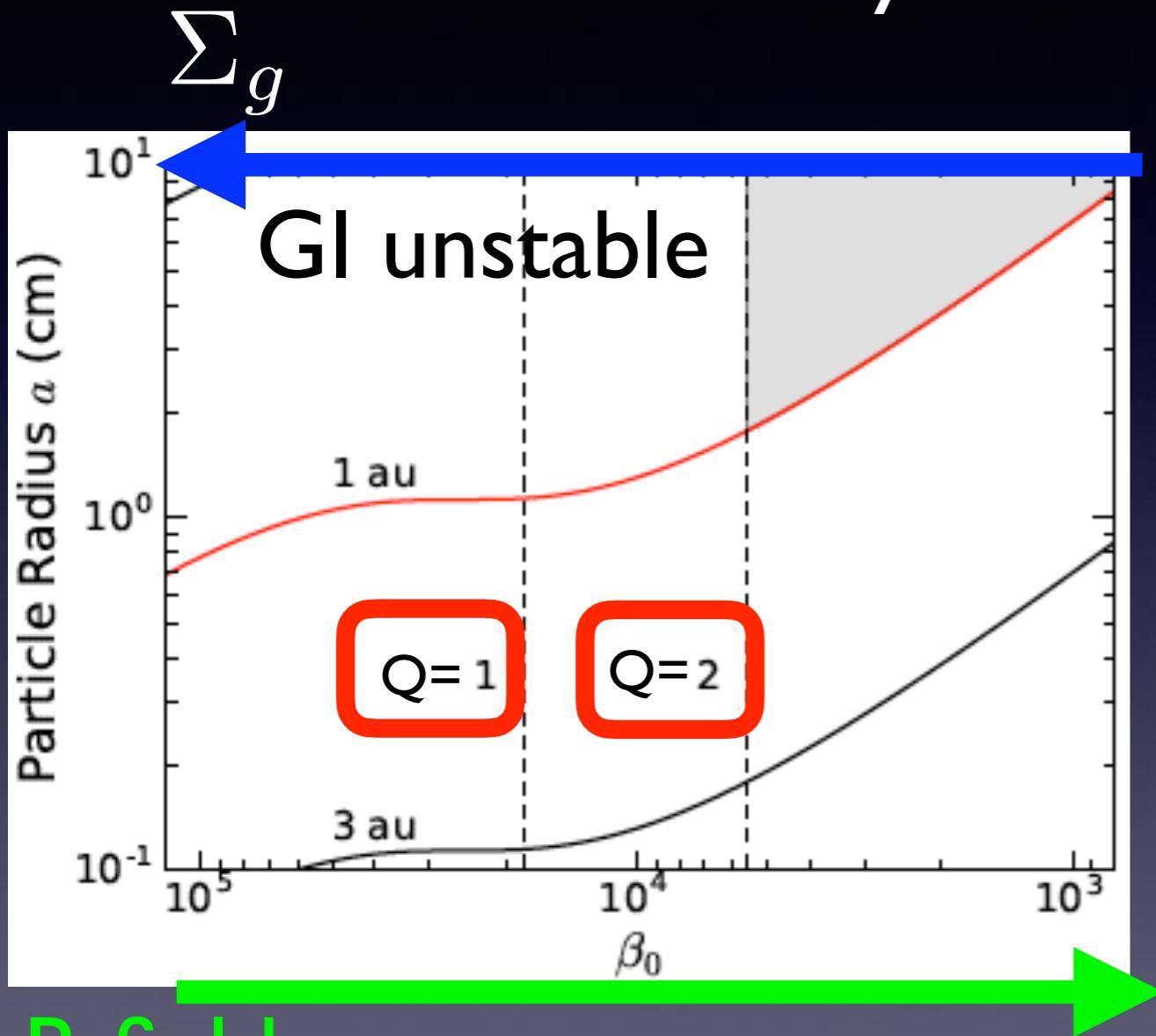
Turbulence only

Turbulence + Winds

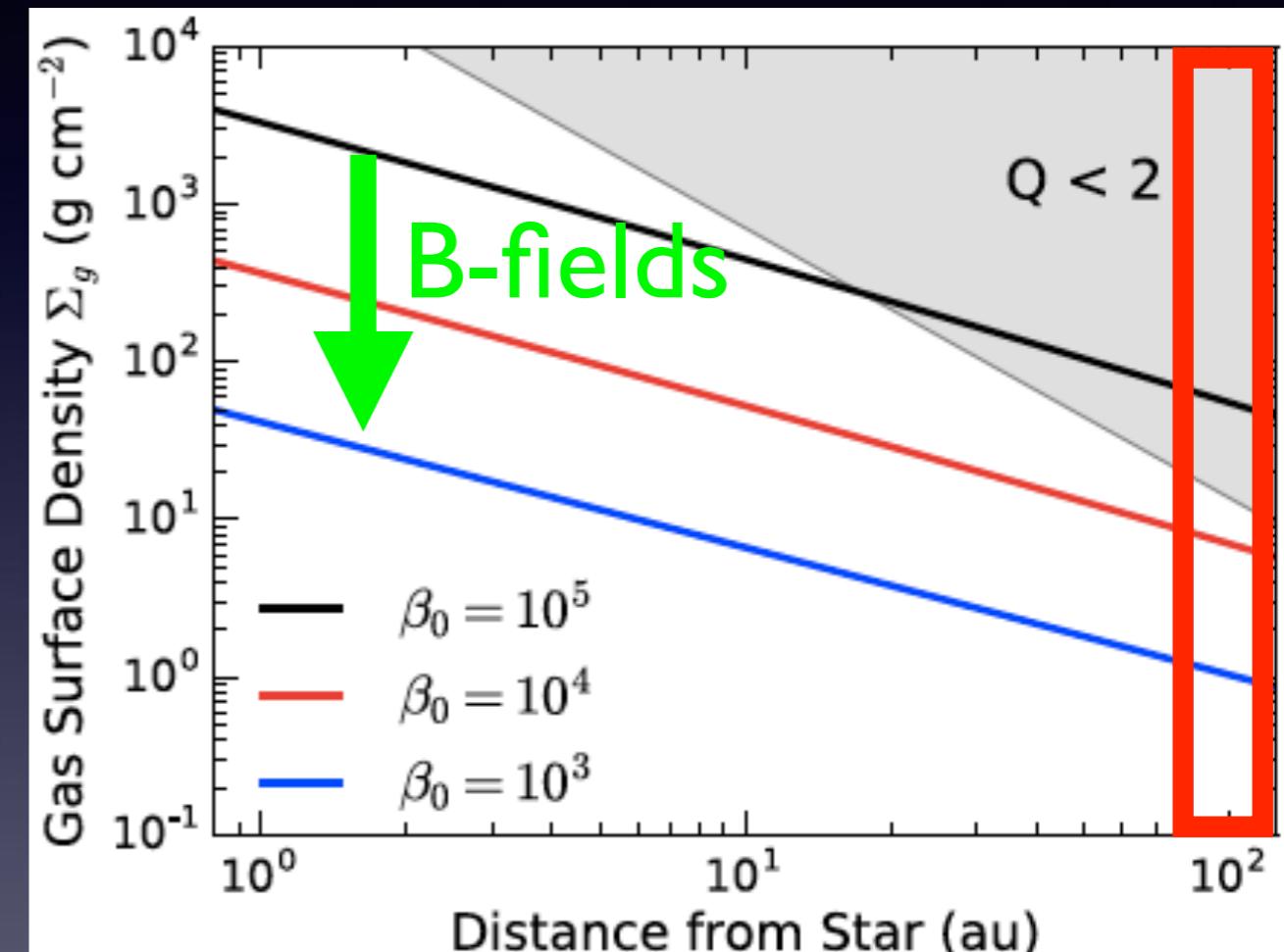
Results are obtained for given values of disk accretion rate, disk temperature

Results at $r = 100$ au

Turbulence only



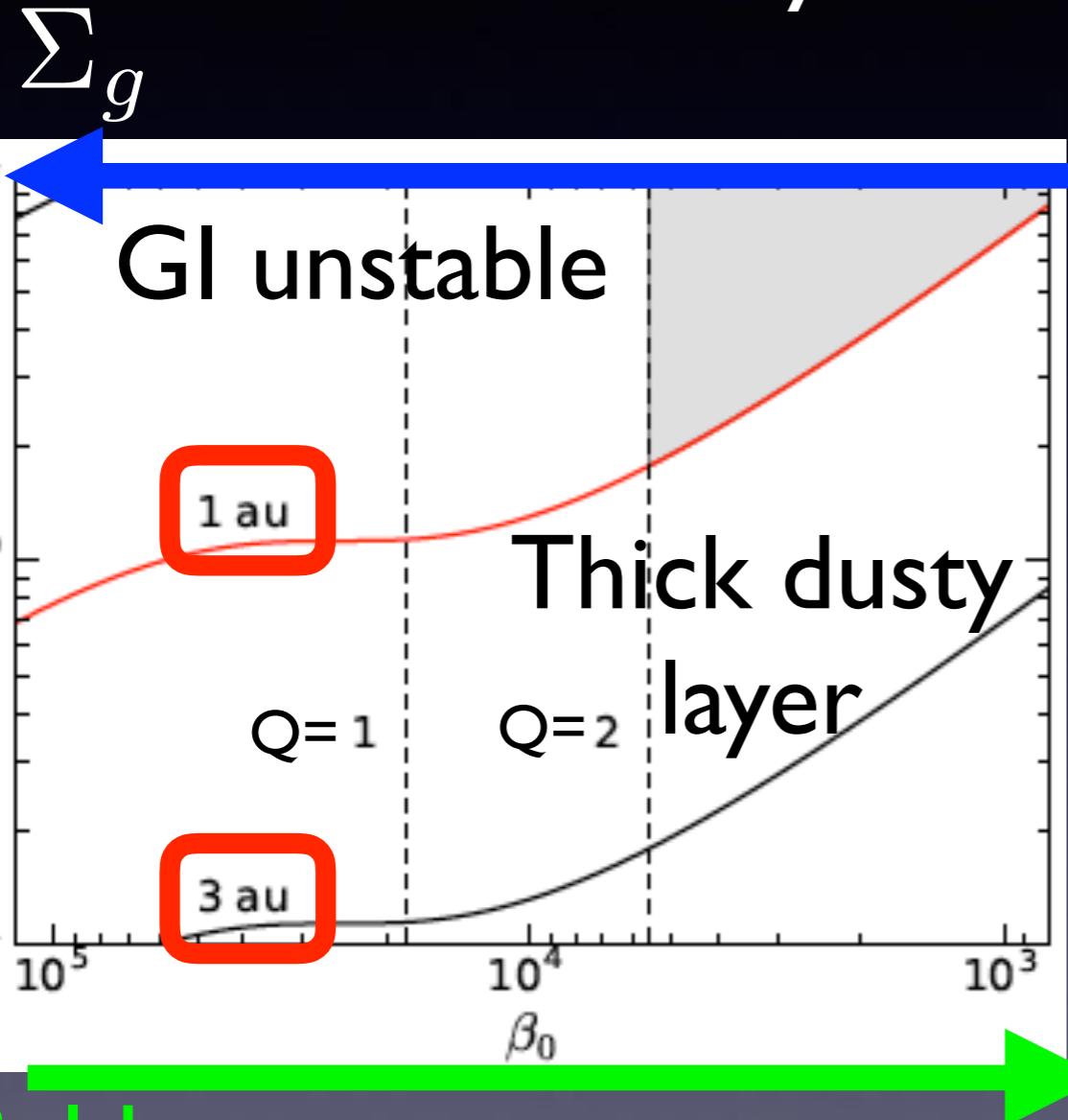
Turbulence + Winds



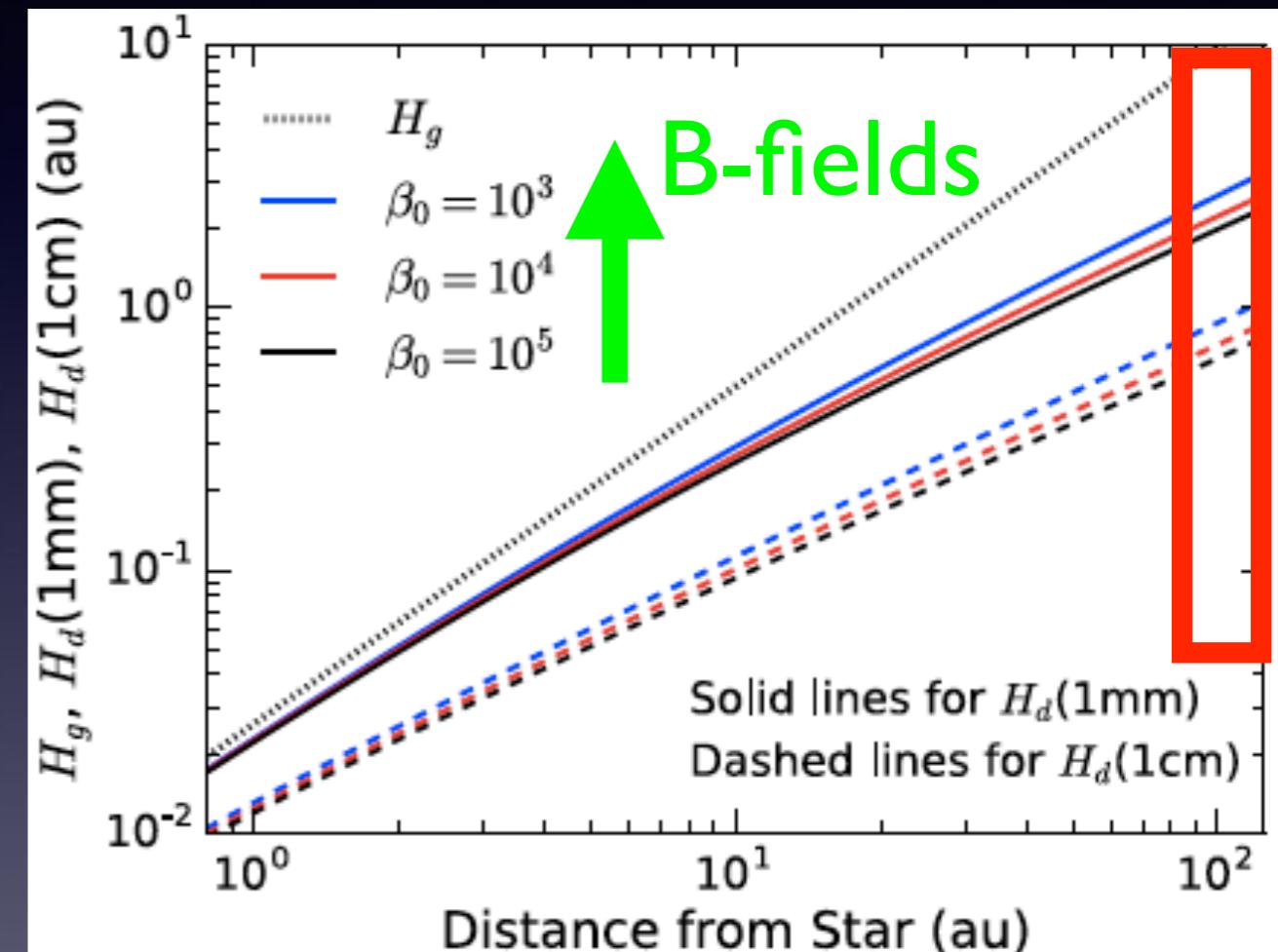
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Results at $r = 100$ au

Turbulence only



Turbulence + Winds

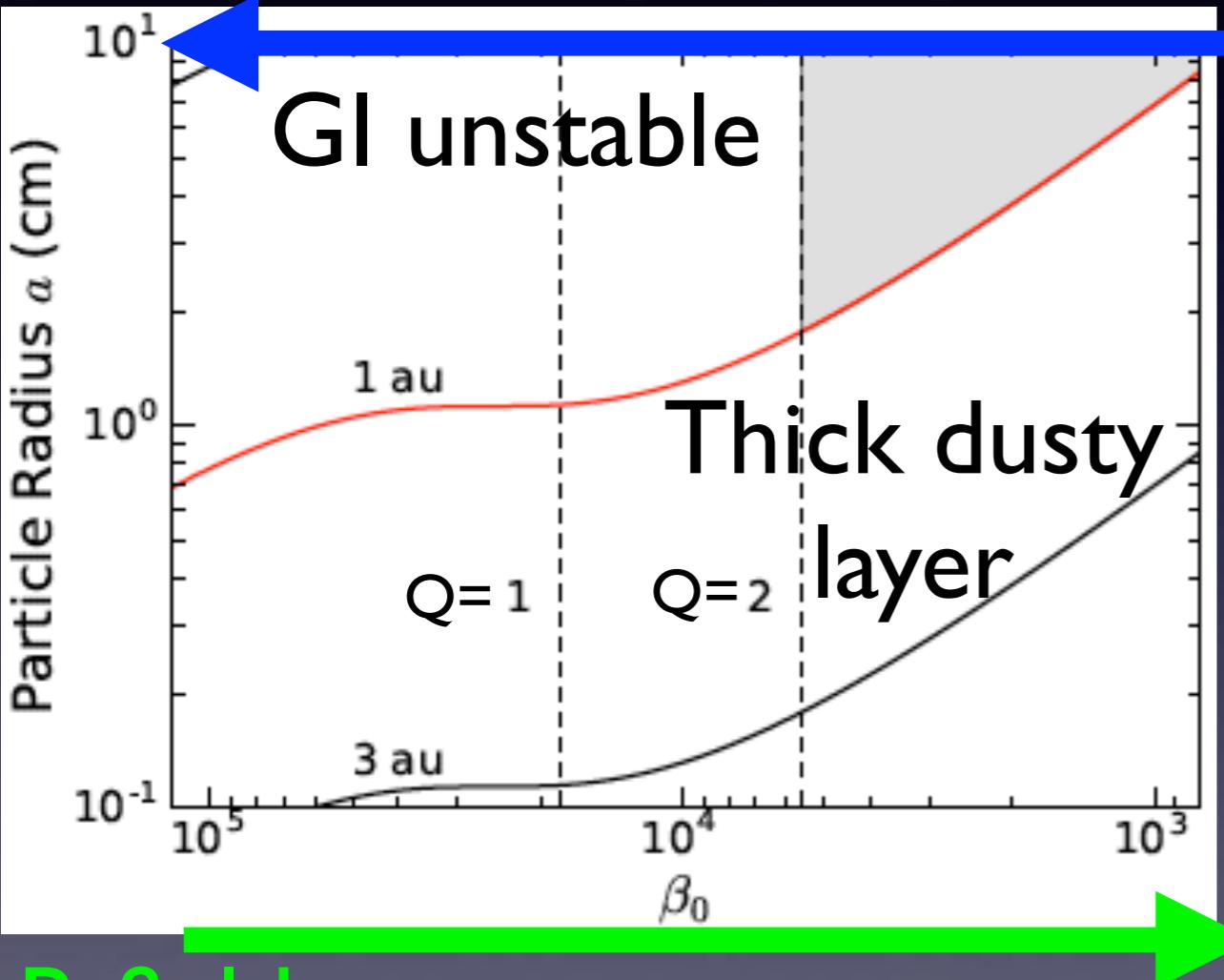


Results are obtained for given values of disk accretion rate, disk temperature

Results at $r = 100$ au

Turbulence only

$$\Sigma_g$$

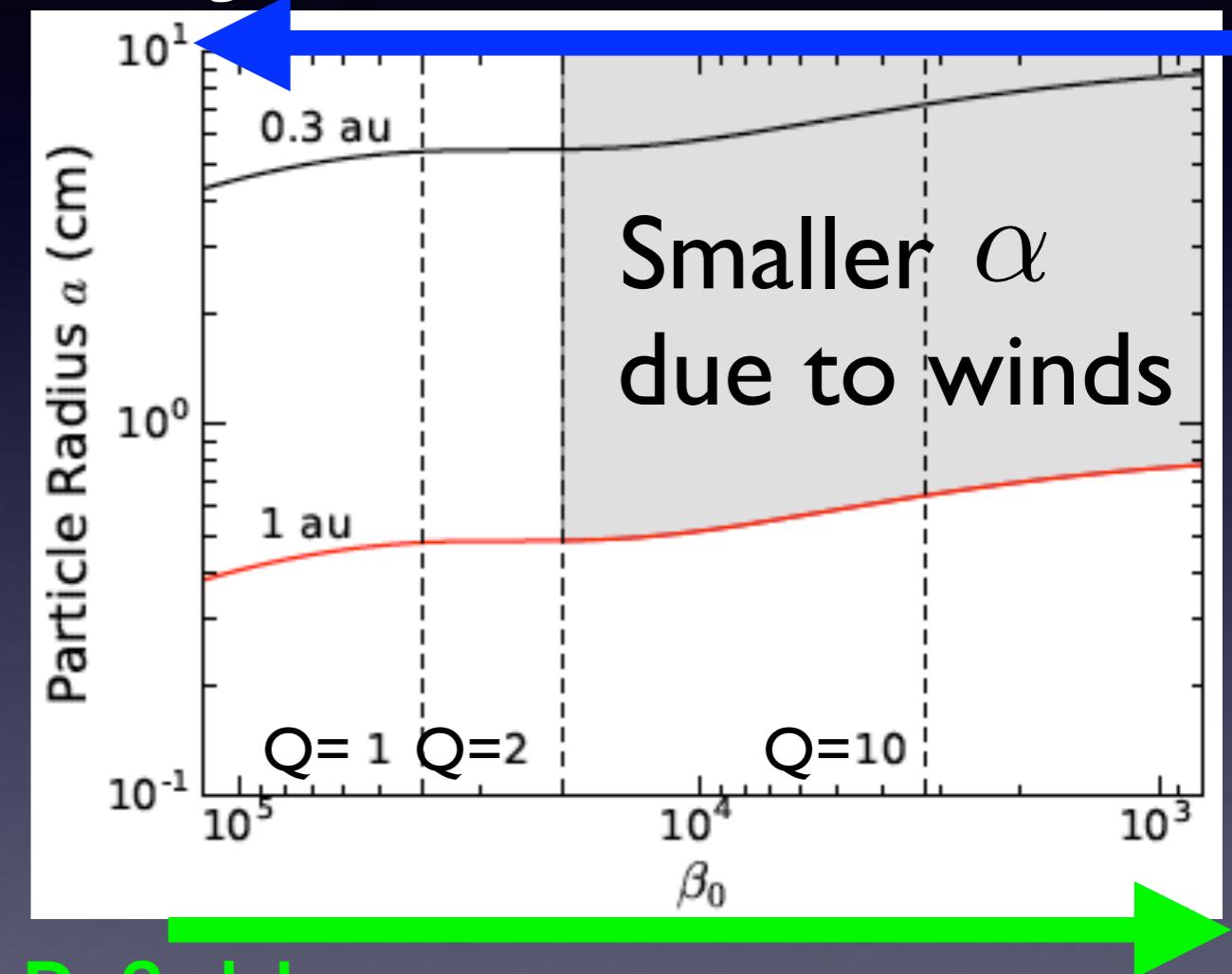


B-fields

20 mm-sized dust is needed
to reproduce ALMA image

Turbulence + Winds

$$\Sigma_g$$

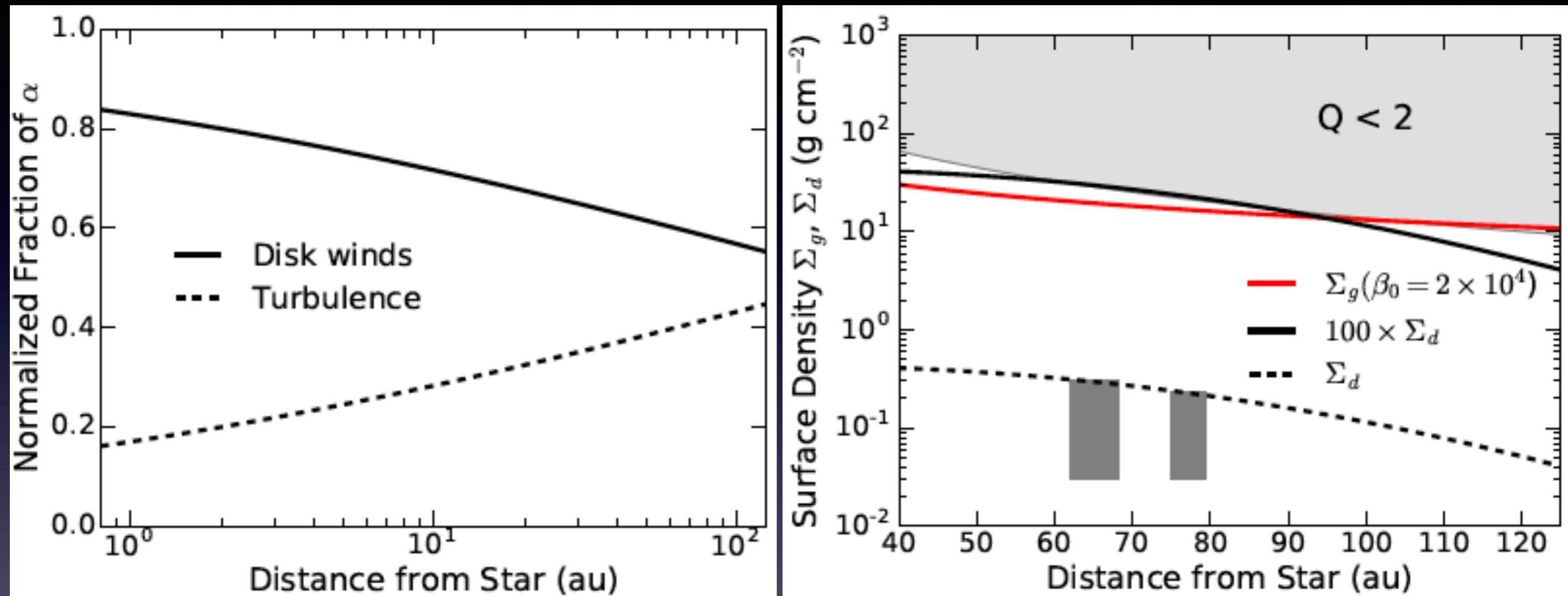


B-fields

4 mm-sized dust is needed
to reproduce ALMA image

Results are obtained for given values of disk accretion rate, disk temperature

Resulting Global Structure of the HL Tau Disk



Disk winds transport the most of angular momentum (50-80 %) across the entire region of the disk

The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

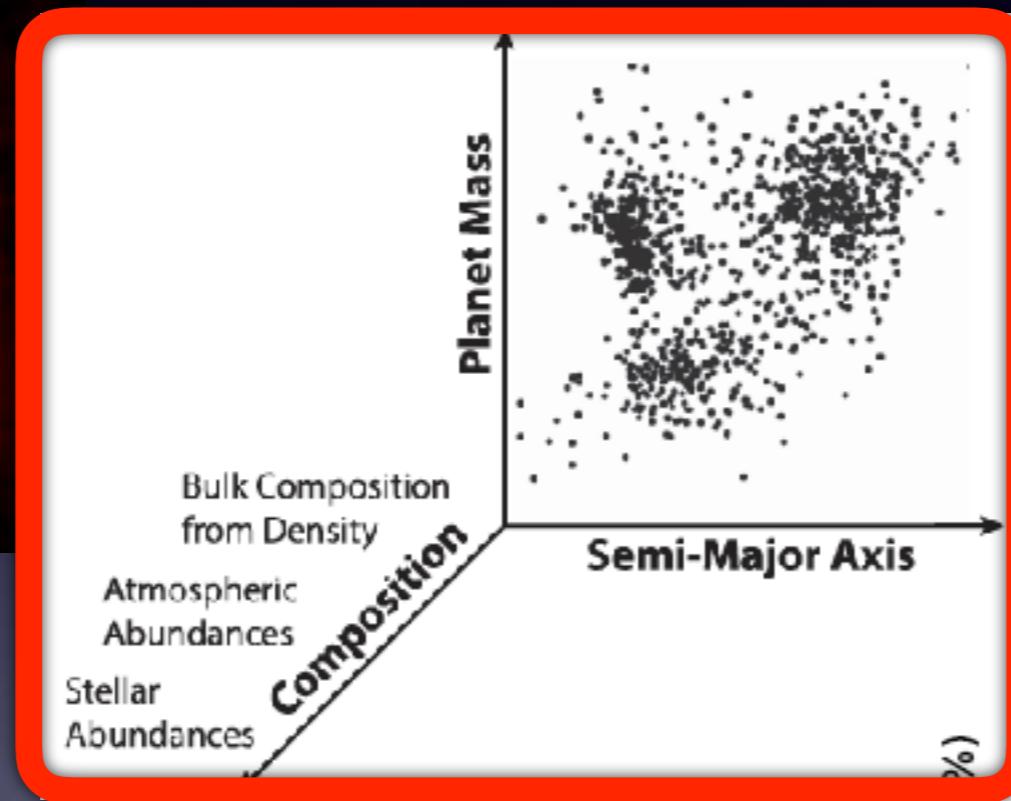
Summary

Hasegawa et al 2017,ApJ, 845, 31

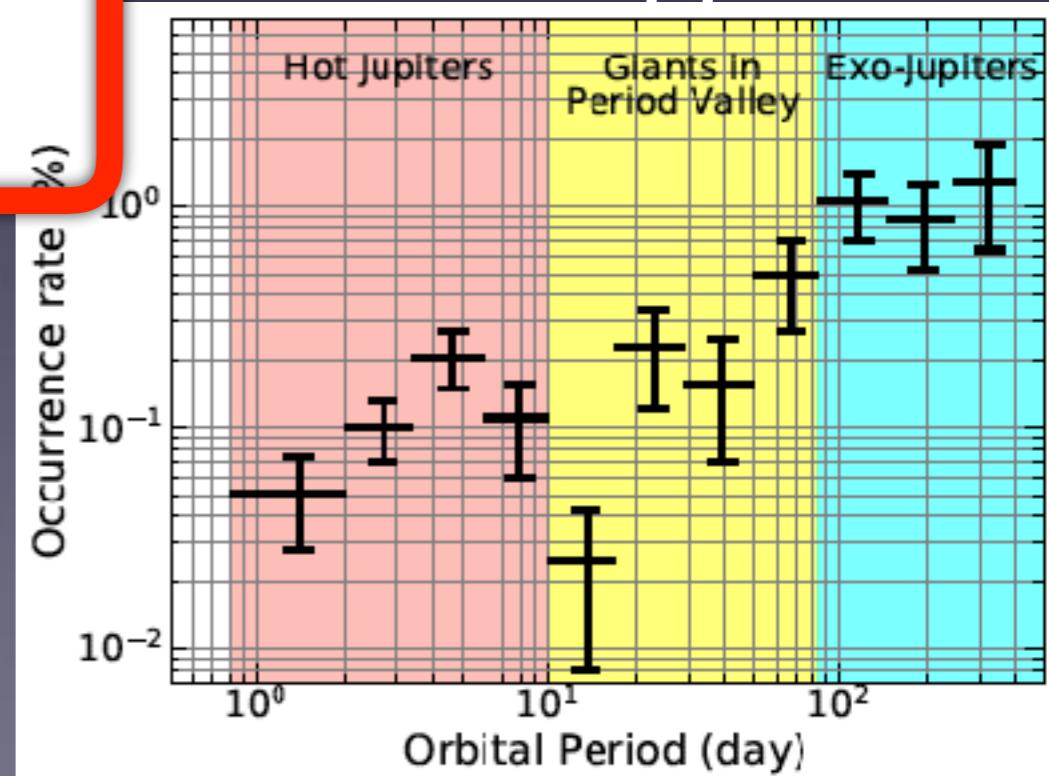
- ALMA observations of the HL Tau disk can advance our understanding of **disk evolution**
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- Our results indicate the importance of **magnetically induced disk winds** to fully reproduce the global configuration
- Followup work will be performed to obtain a better understanding of **polarization** observations and to identify the origins of observed **multiple gaps** in the HL Tau disk

New Disk Model

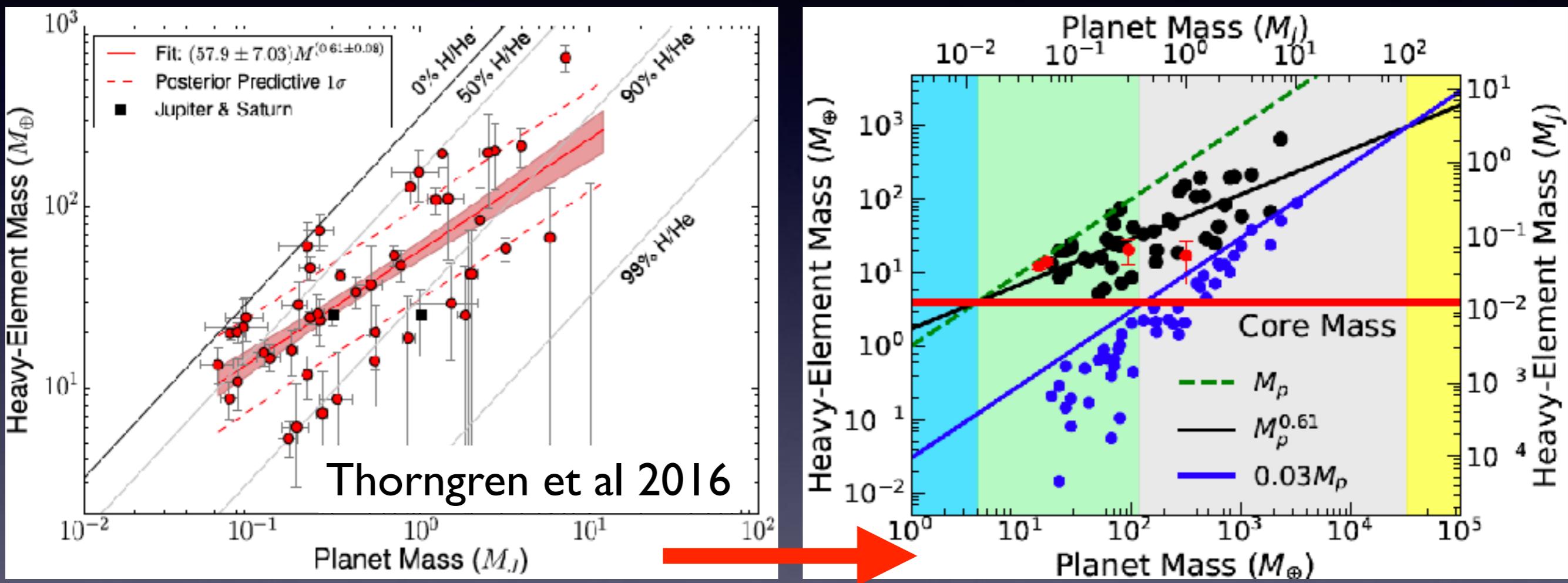
Composition of planets



Retrieval approach

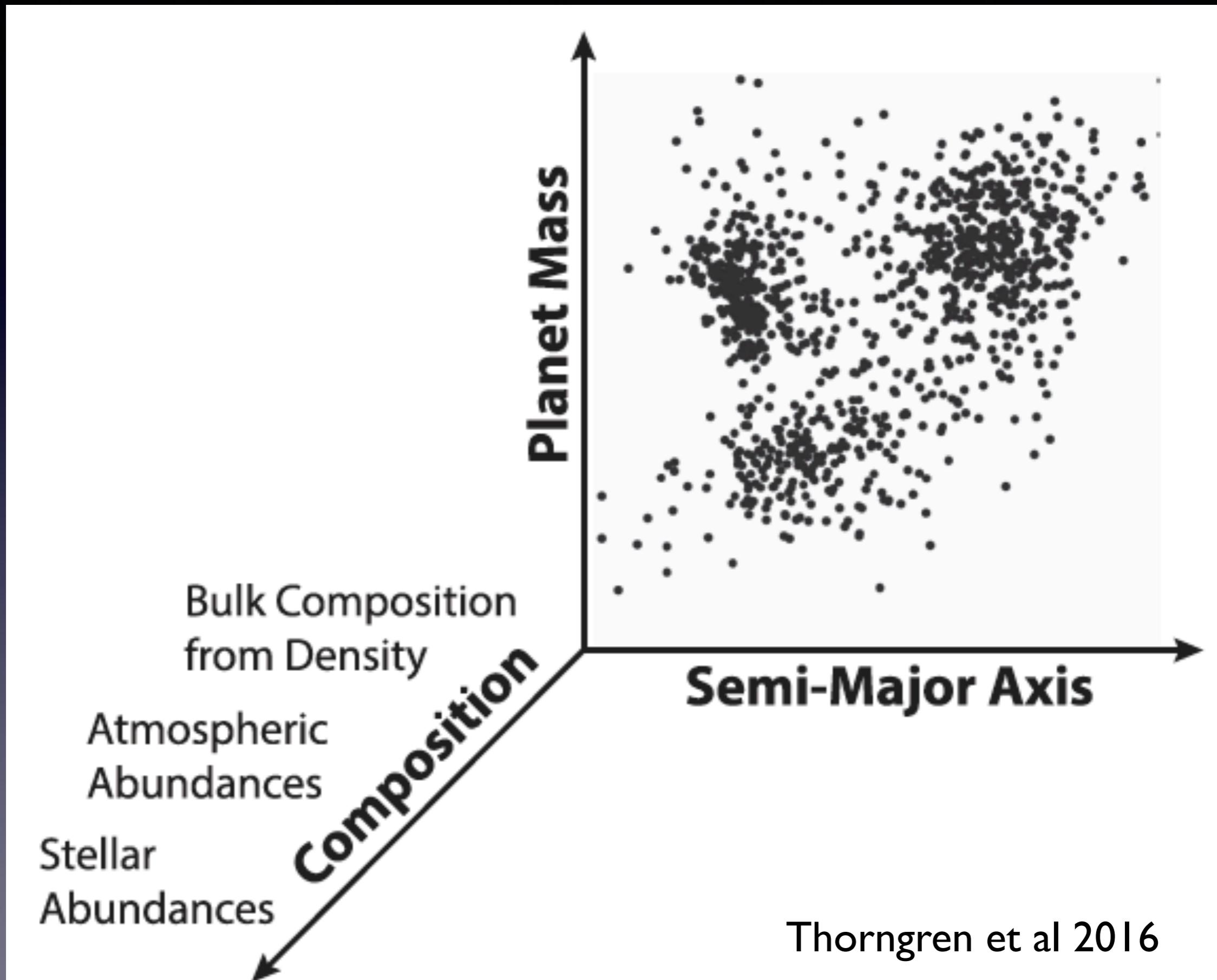


The Origin of the Heavy Element Content Trend in Giant Planets



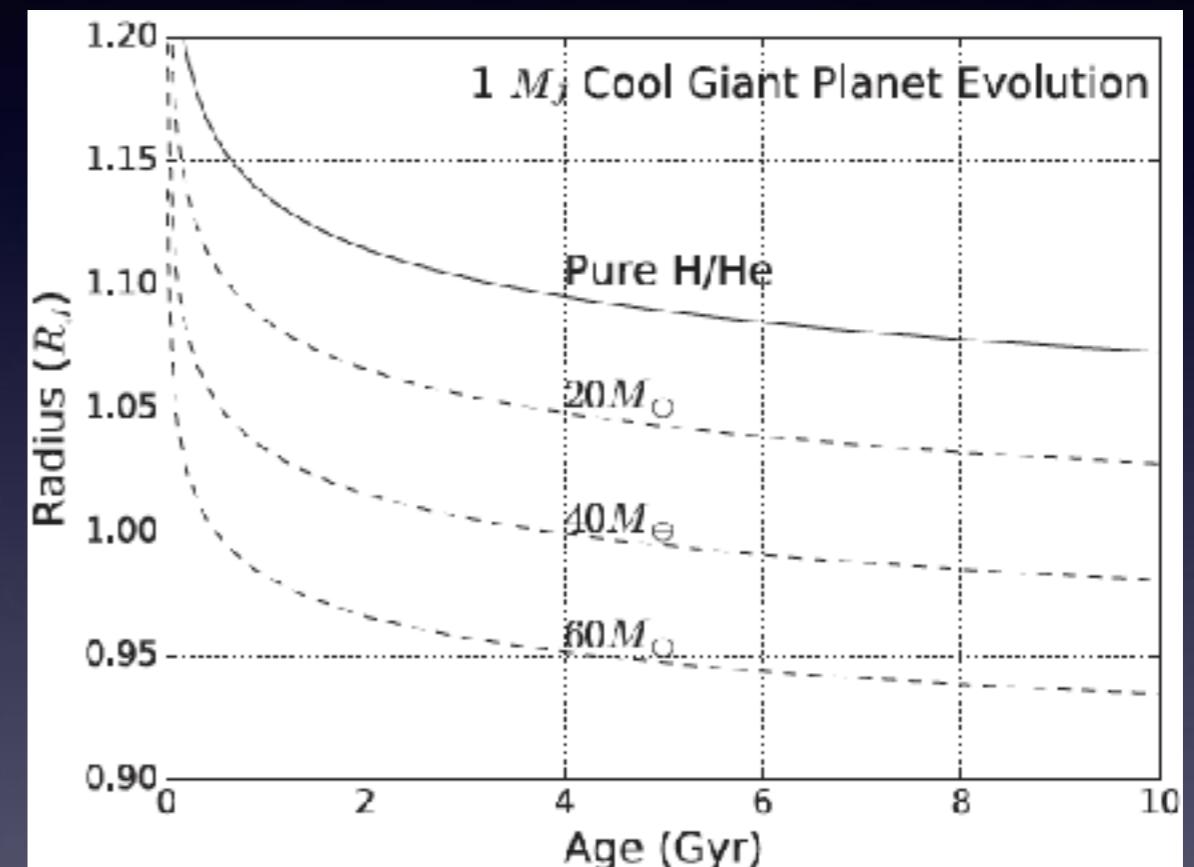
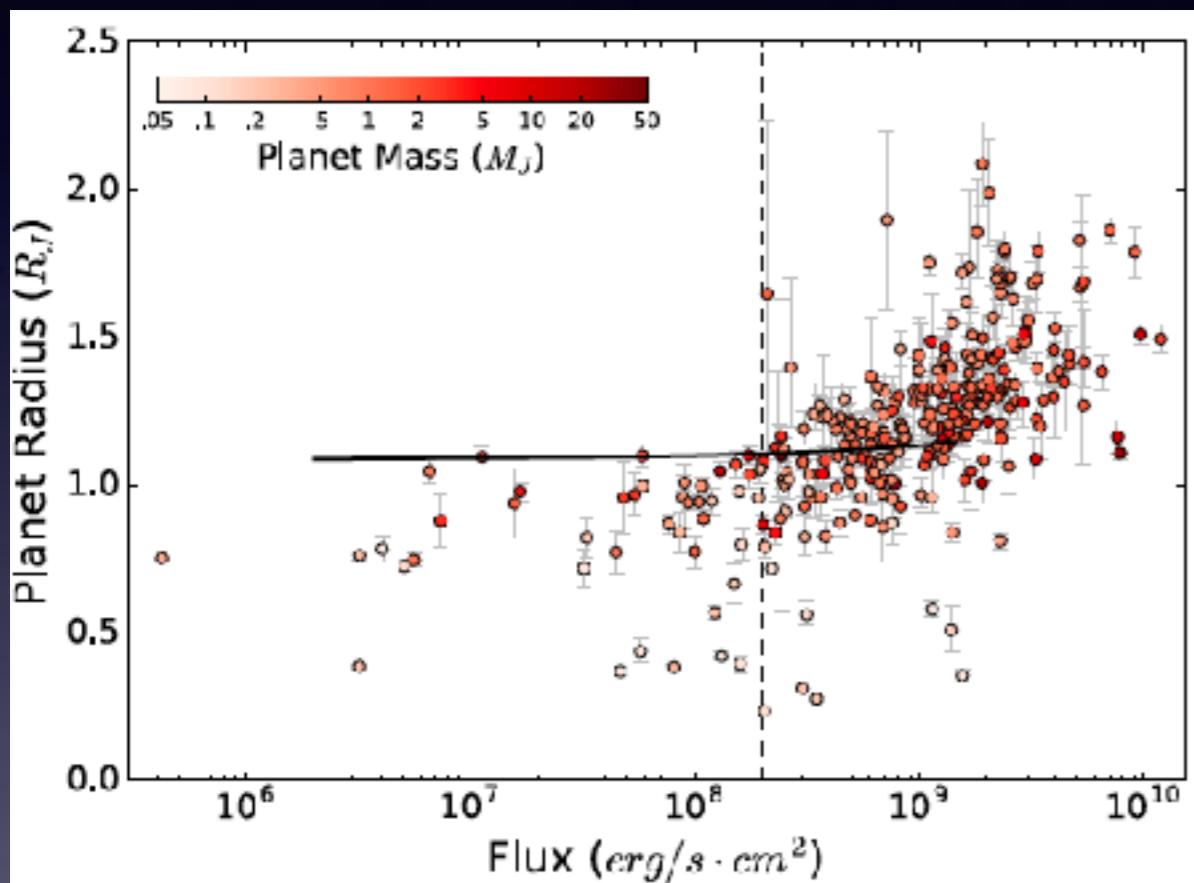
in collaboration with
Geoff Bryden (JPL), Masahiro Ikoma (Univ of Tokyo),
Gautam Vasisht (JPL), Mark Swain (JPL)

How do Planets form?



Estimate of the heavy element mass in observed exoplanets

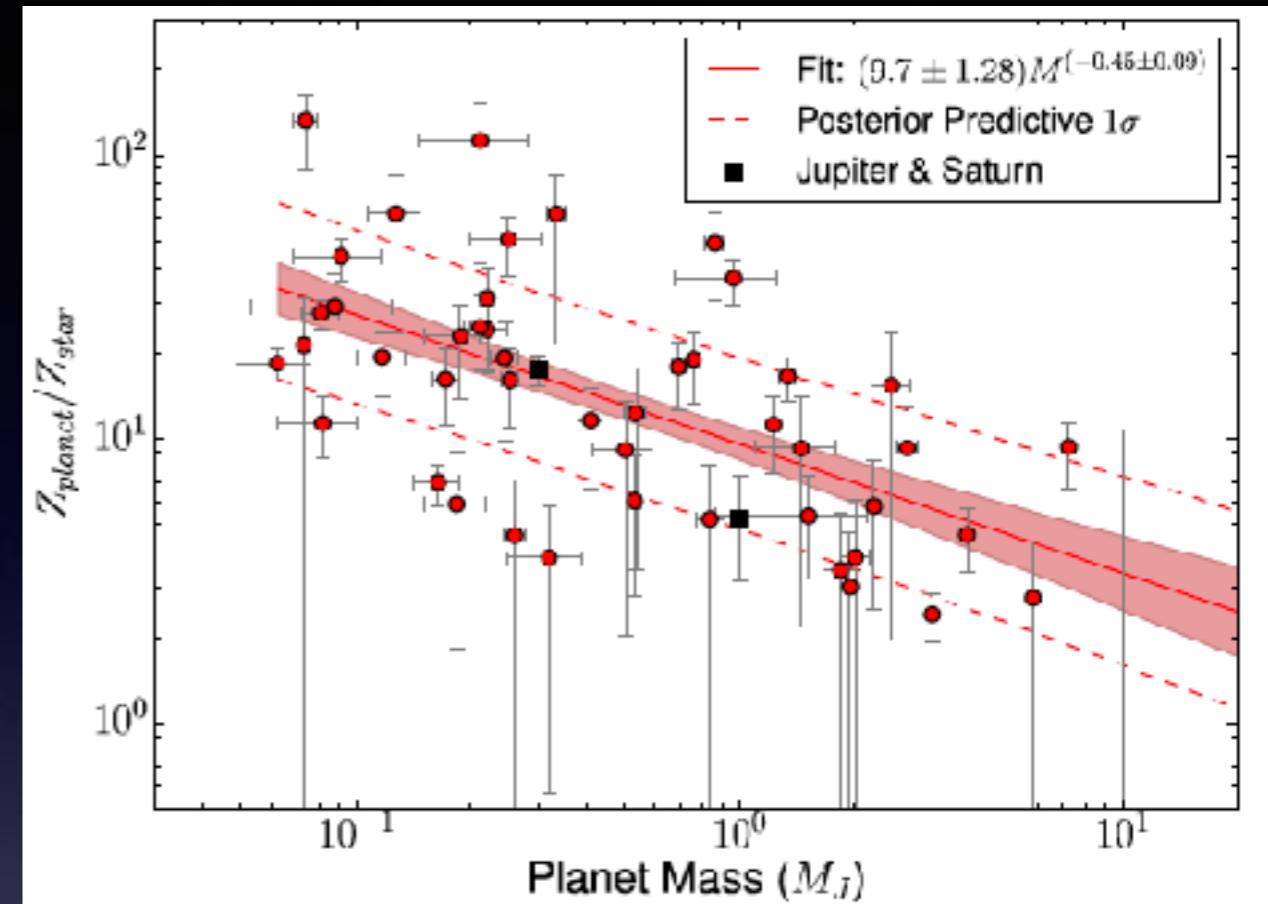
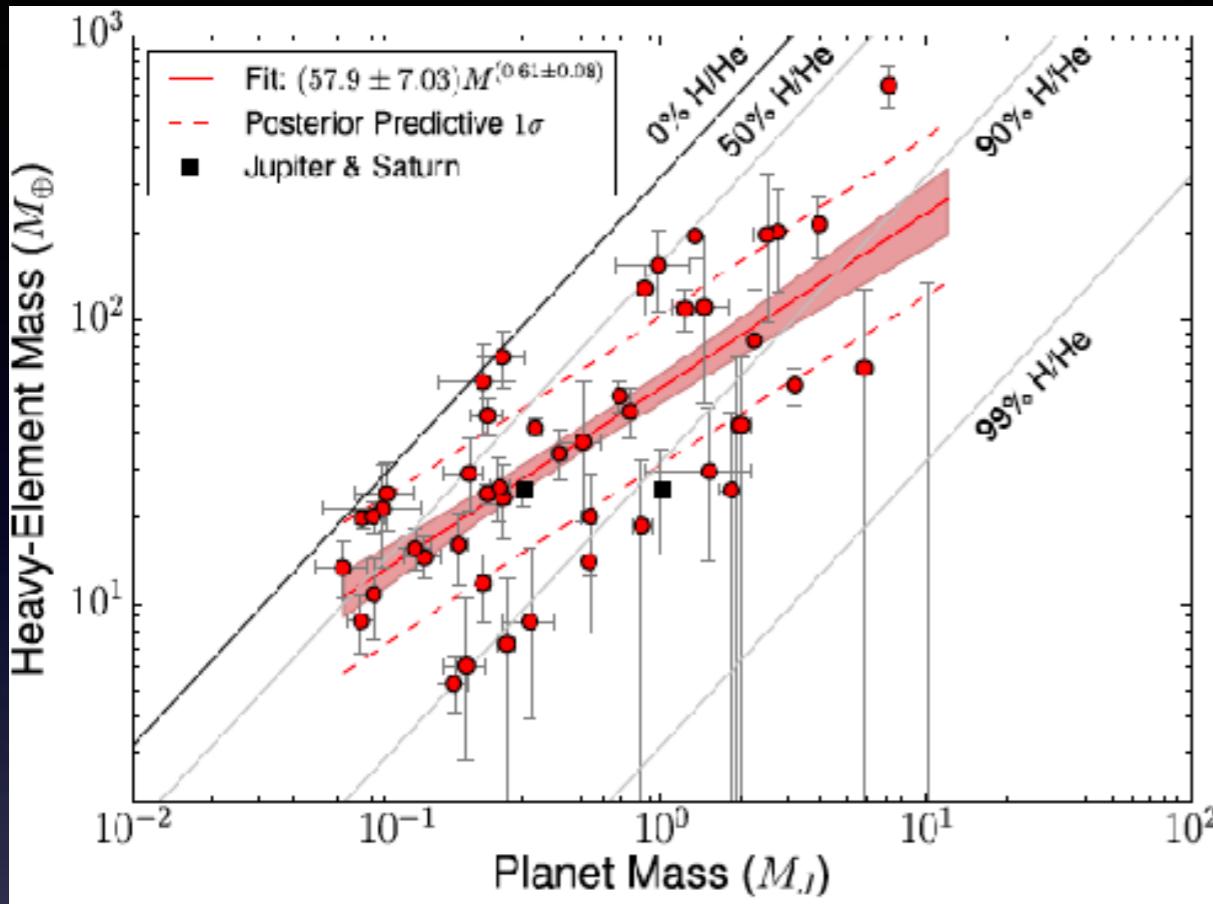
e.g., Guillot et al 2006; Miller & Fortney 2011; Thorngren et al 2016



Target selection: relatively cool close-in exoplanets

Distribute heavy elements in cores and envelopes,
and compute the radius evolution of planets

Results of Thorngren et al 2016 (T16)



$$M_Z \propto M_p^\Gamma \text{ with } \Gamma = 0.61 \pm 0.08 \simeq 3/5$$

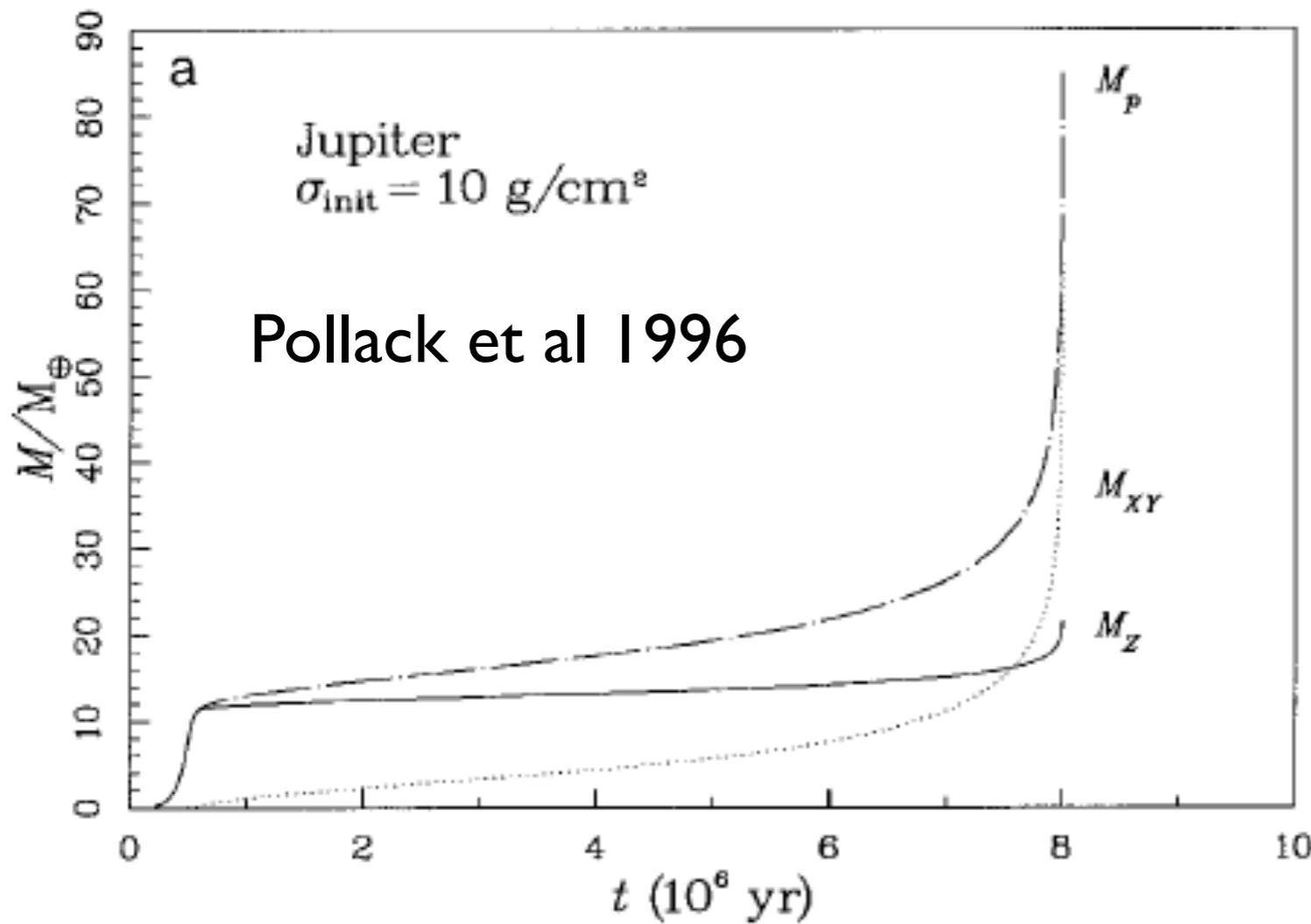
$$\frac{Z_p}{Z_s} = \frac{M_Z}{M_p Z_s} \propto M_p^\beta \text{ with } \beta = -0.45 \pm 0.09 \simeq -2/5$$

$\Gamma - 1 \simeq \beta \Rightarrow M_Z$ and M_p are almost independent of Z_s

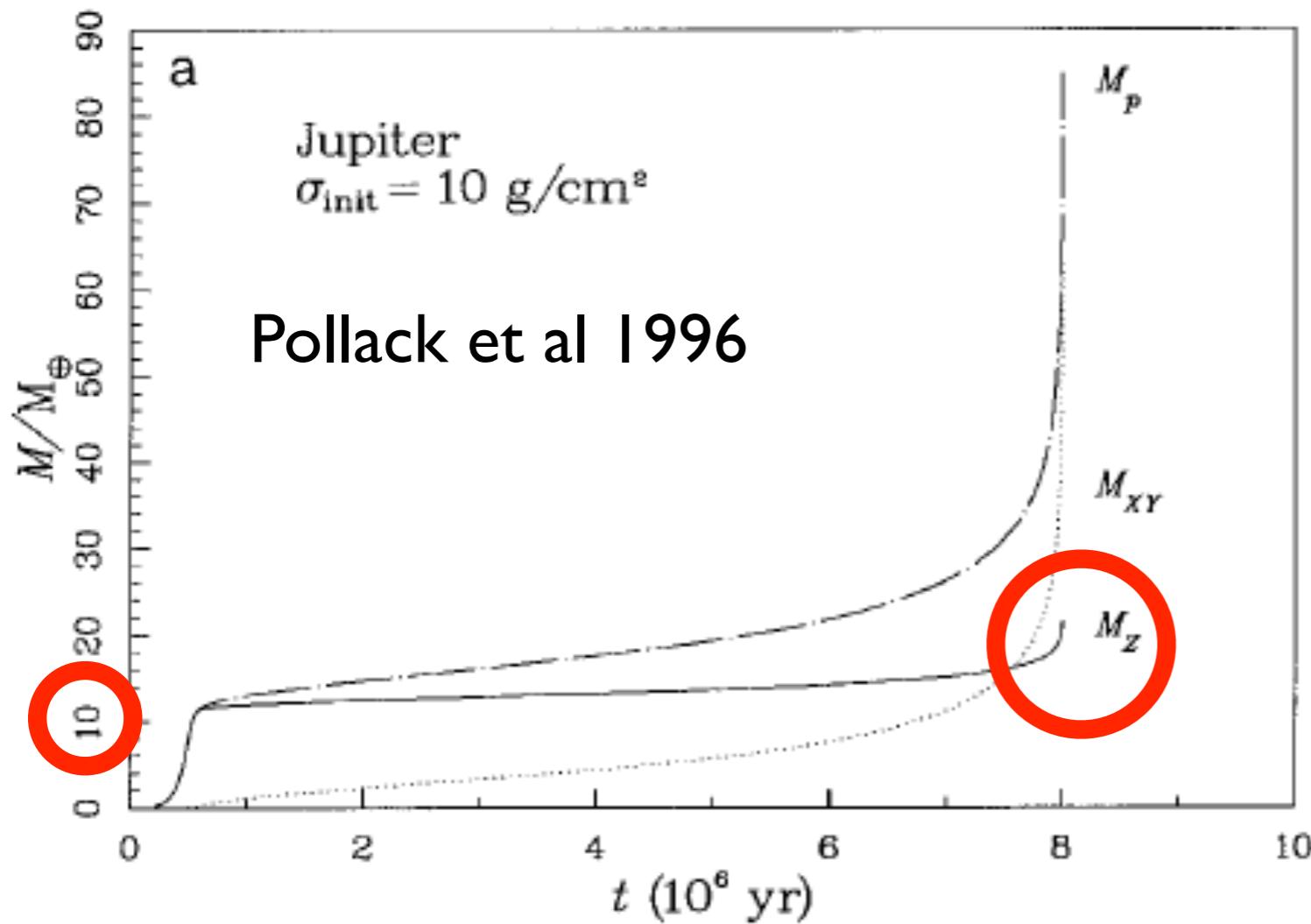
M_Z : the total heavy element mass in planets with the mass of M_p

Z_s : the metallicity of the host star

Planet Formation via Core Accretion: Accretion of Gas and Solids



Planet Formation via Core Accretion: Accretion of Gas and **Solids**

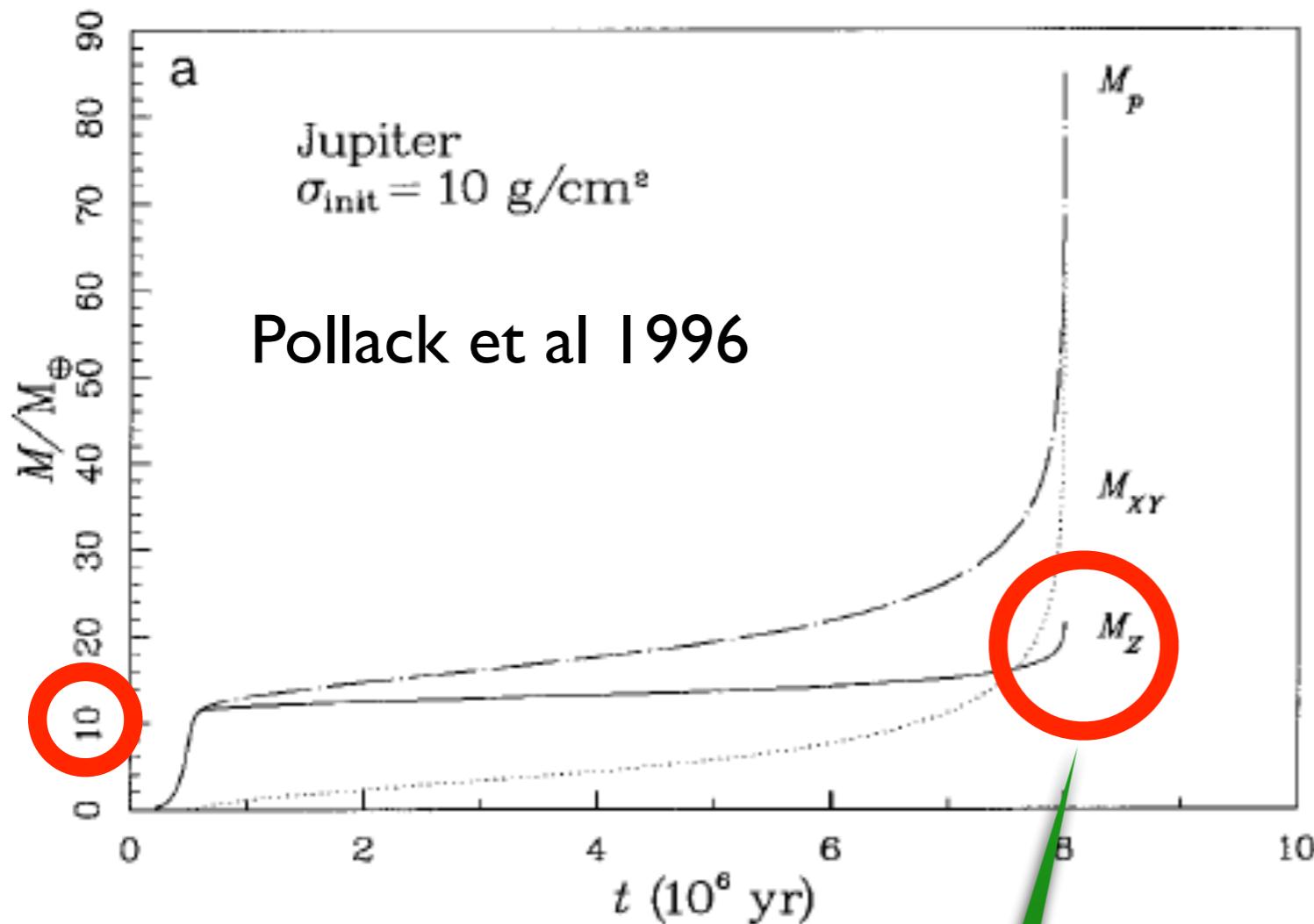


$$M_{\text{core}} \simeq 10M_\oplus$$

M_z increases at the final formation stage



Planet Formation via Core Accretion: Accretion of Gas and **Solids**



$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{\text{core}} + M_{\text{pl}} + M_{\text{pe}} + M_{Z,\text{gas}}$$

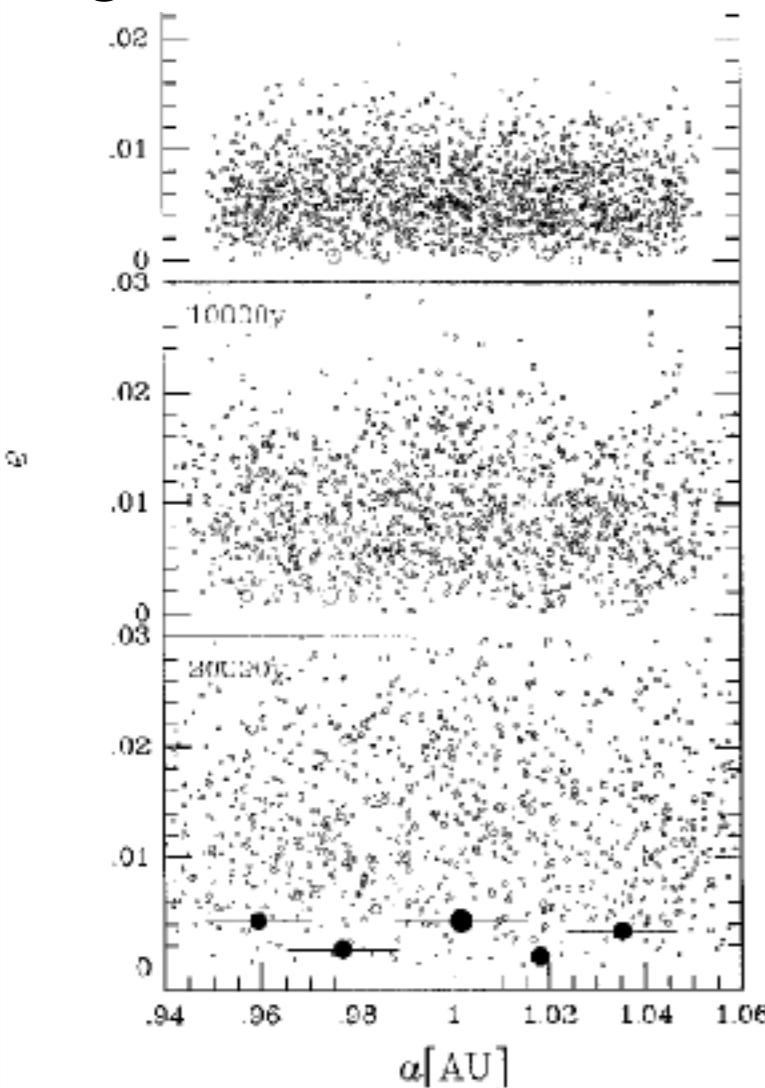
Planetsimals

Pebbles

dust in gas



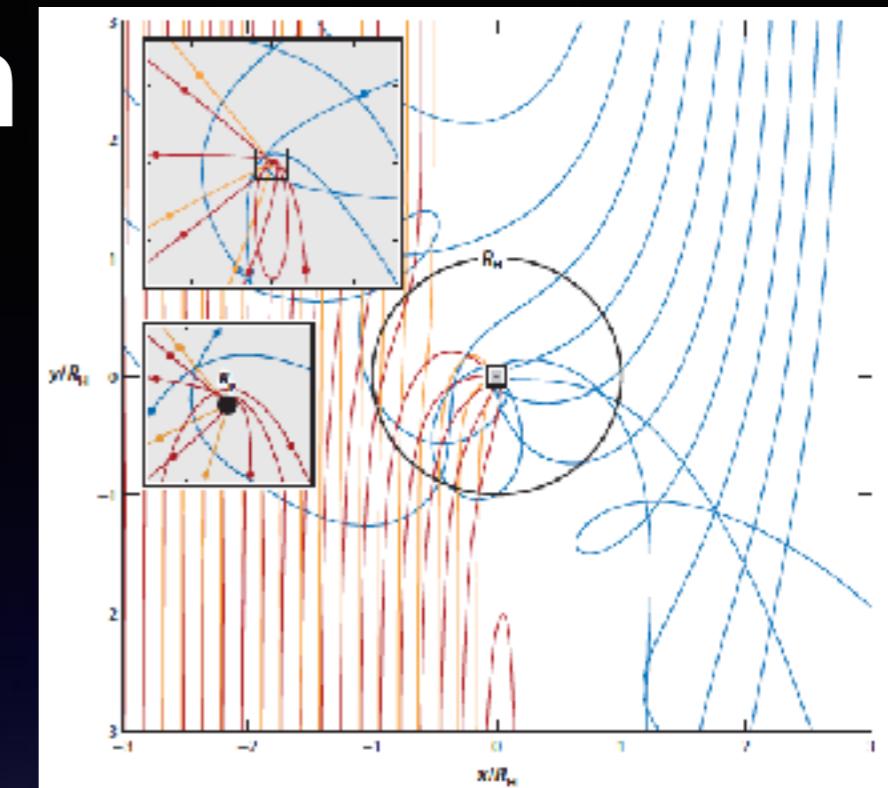
e.g., Kokubo & Ida 2000



Core formation

Oligarchic growth

Pebble accretion



e.g., Johansen & Lambrechts 2017

M_{core} :determined by disk properties
:independent of M_p

$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planetesimals

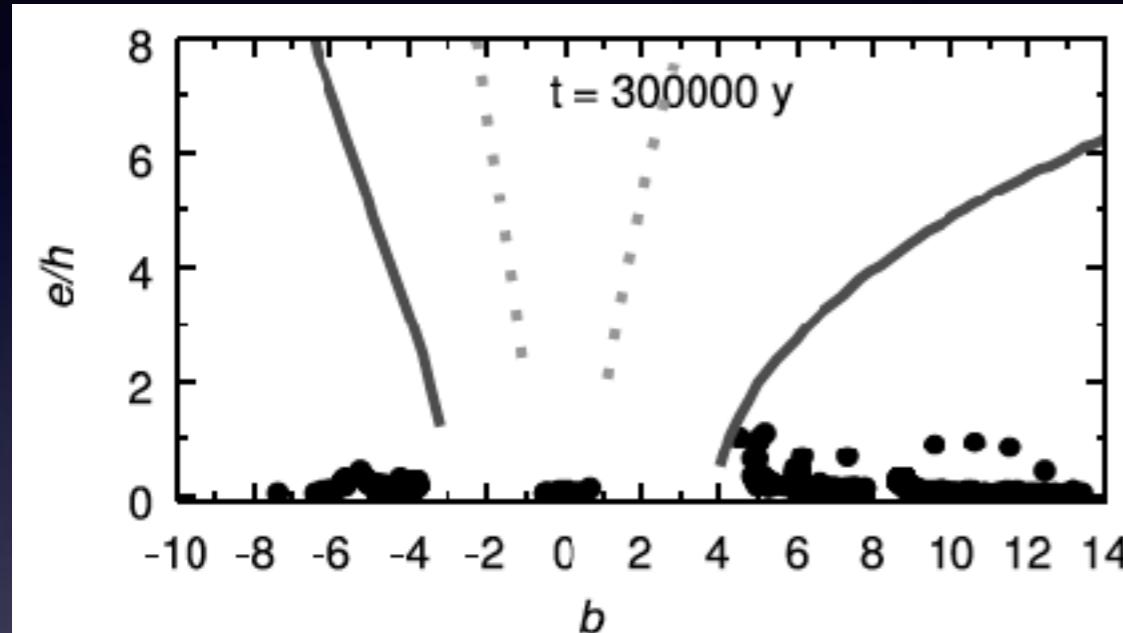
Pebbles

dust in gas

Planetesimal Accretion

$$\frac{dM_{pl}}{dt} \propto M_p^{2/5} \tau_{g,acc}^{-4/5}$$

without planetesimal gaps



$$\frac{dM_{pl}}{dt} \propto M_p^{13/30} \tau_{g,acc}^{-7/5}$$

with planetesimal gaps

$$M_p = M_{XY} + M_Z$$

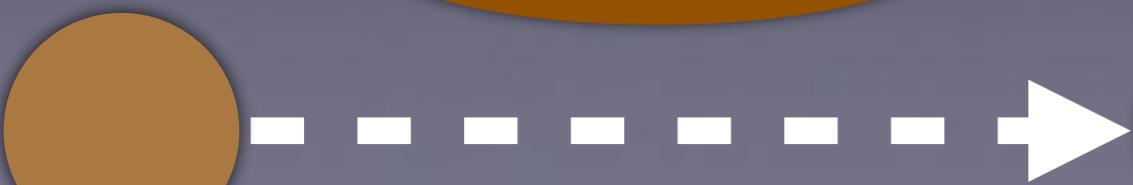
$\tau_{g,acc}$: gas accretion timescale

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planetesimals

Pebbles

dust in gas



Pebble Accretion

The final formation stage is out of the scope of recent studies

$$\frac{dM_{pe}}{dt} \propto M_p^{2/3}$$

the Hill regime is considered

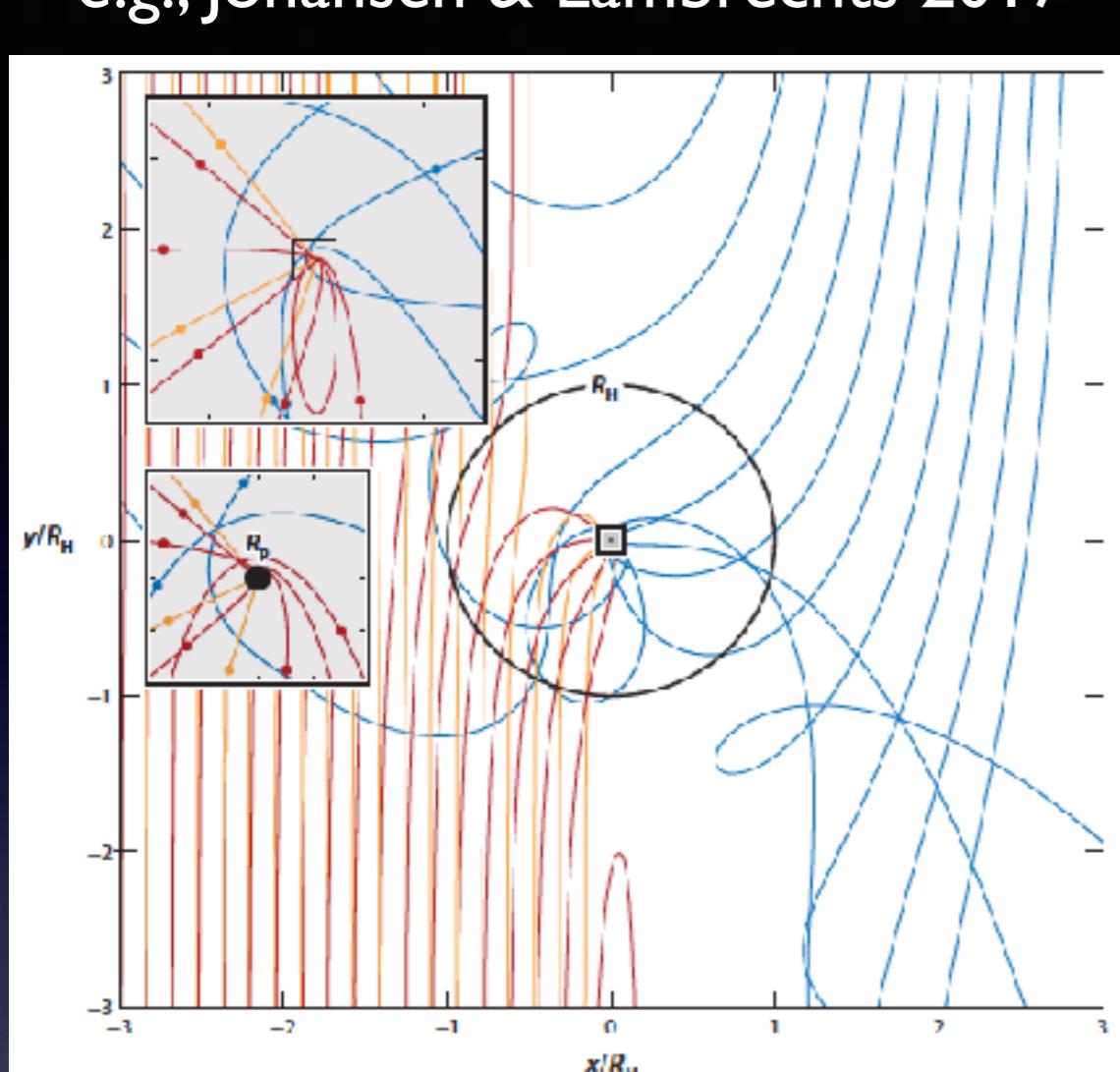
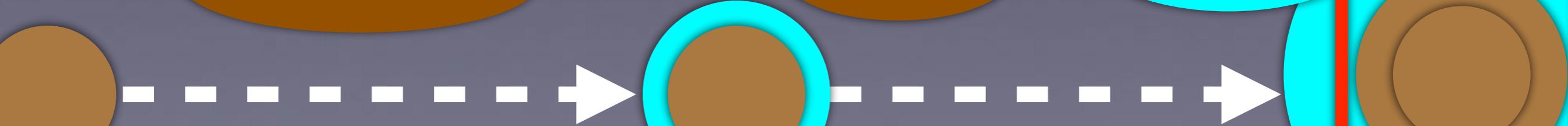
$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planетесimals

Pebbles

dust in gas

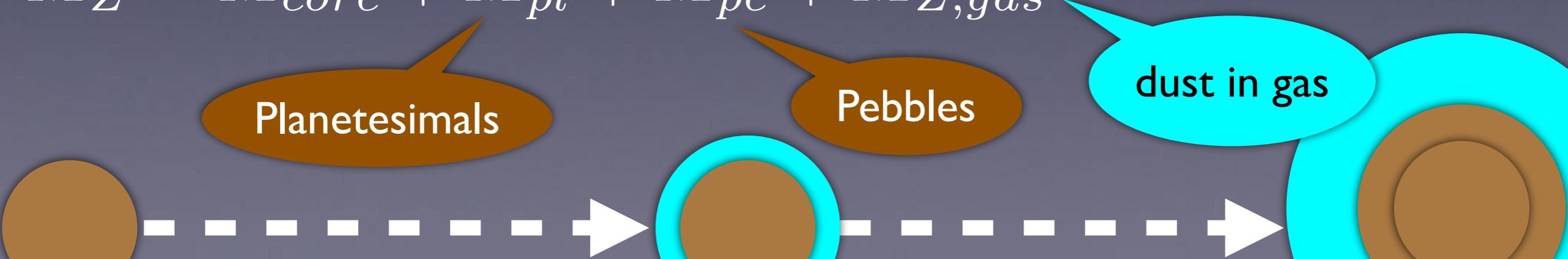


Power-law index	T16	M_{core}	M_{pl} (w/o Gap)	M_{pl} (w/ Gap)	M_{pe}
$\Gamma(M_Z \propto M_p^\Gamma)$	3/5	0	1/3	3/5	1/3
$\beta(Z_p \propto M_p^\beta)$	-2/5	-1	-2/3	-2/5	-2/3

Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

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Planetsimals

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Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007

Planets accreted solids from **gapped** planetesimal disks
at the **final** formation stage

$$M_p = M_{XY} + M_Z$$

$$M_Z = \cancel{M_{core}} + \circled{M_{pl}} + \cancel{M_{pe}} + M_{Z,gas}$$

Planetesimals

Pebbles

dust in gas



Dust accretion accompanying with gas accretion

$$\begin{aligned}M_{Z,gas} &= Z_s M_{XY} \\&= Z_s (M_p - M_Z)\end{aligned}$$

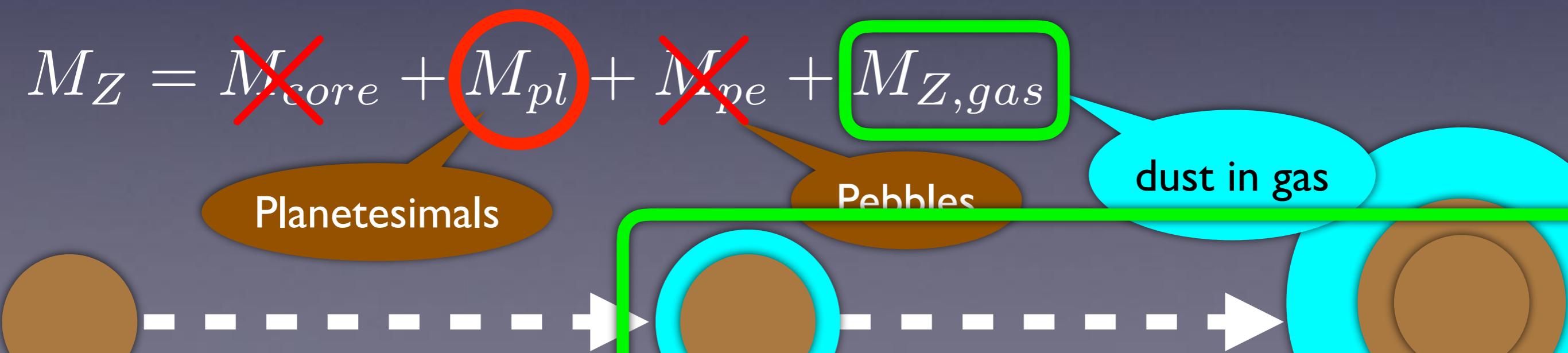
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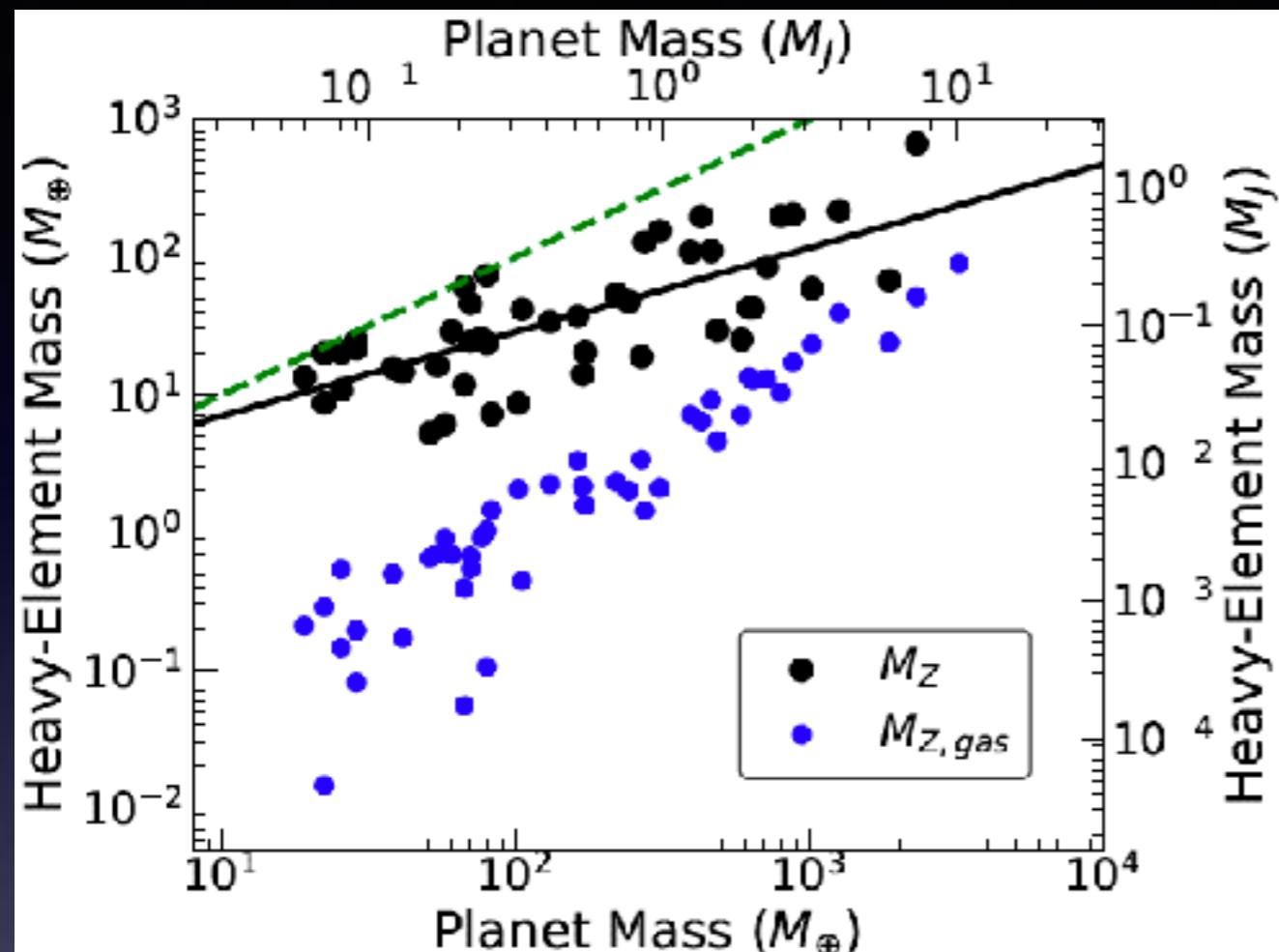
Planetsimals

Pebbles

dust in gas



Dust accretion accompanying with gas accretion



$$M_{Z,gas} = Z_s M_{XY}$$
$$= Z_s (M_p - M_Z)$$

Contribution arising from
gas accretion is negligible

$$M_p = M_{XY} + M_Z$$

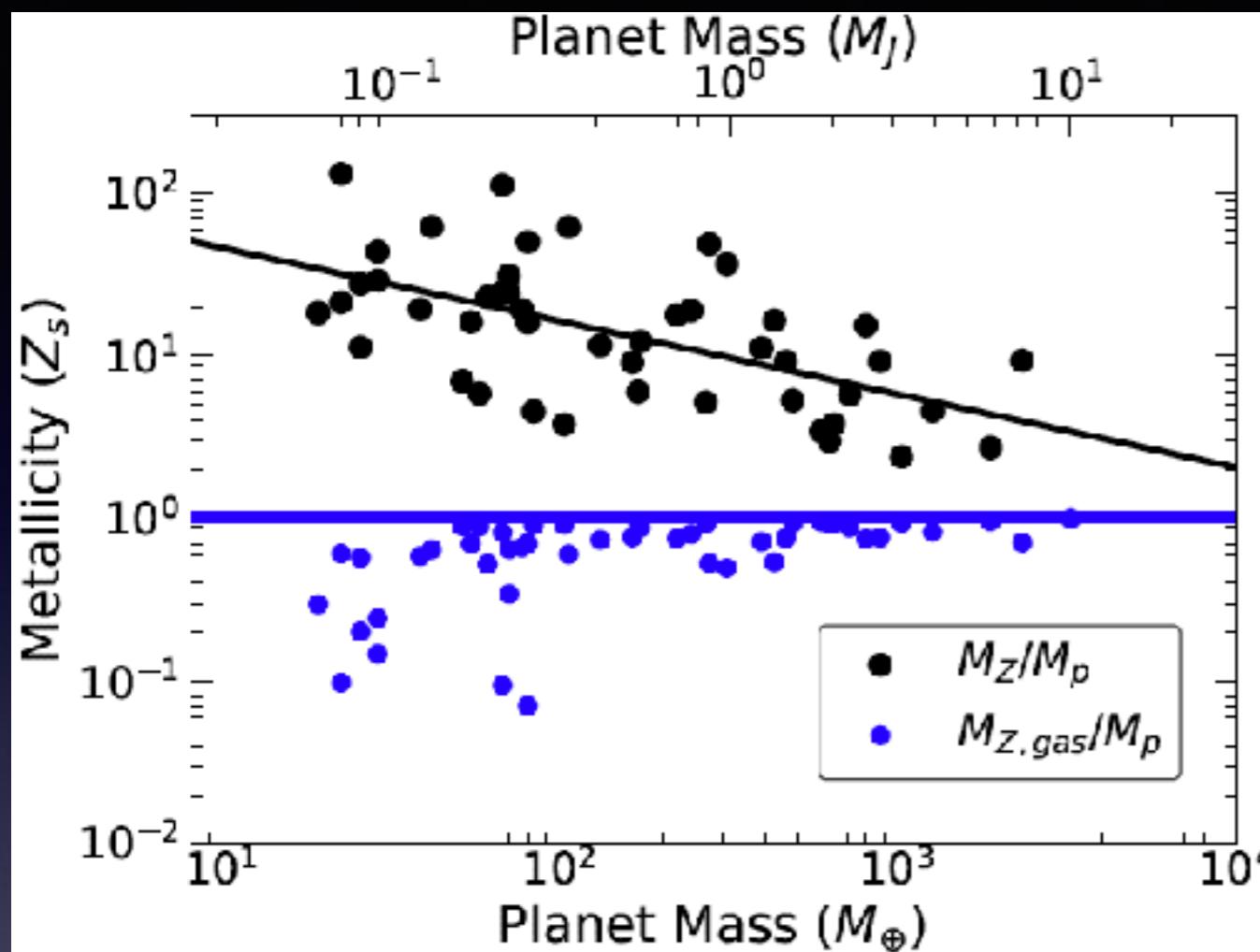
$$M_Z = \cancel{M_{core}} + \cancel{M_{pl}} + \cancel{M_{pe}} + M_{Z,gas}$$

Planets

Pebbles

dust in gas

Dust accretion accompanying with gas accretion



$$\begin{aligned} M_{Z,gas} &= Z_s M_{XY} \\ &= Z_s (M_p - M_Z) \end{aligned}$$

Contribution arising from gas accretion is negligible

The dust abundance in the accreted gas is similar to Z_s

$$M_p = M_{XY} + M_Z$$

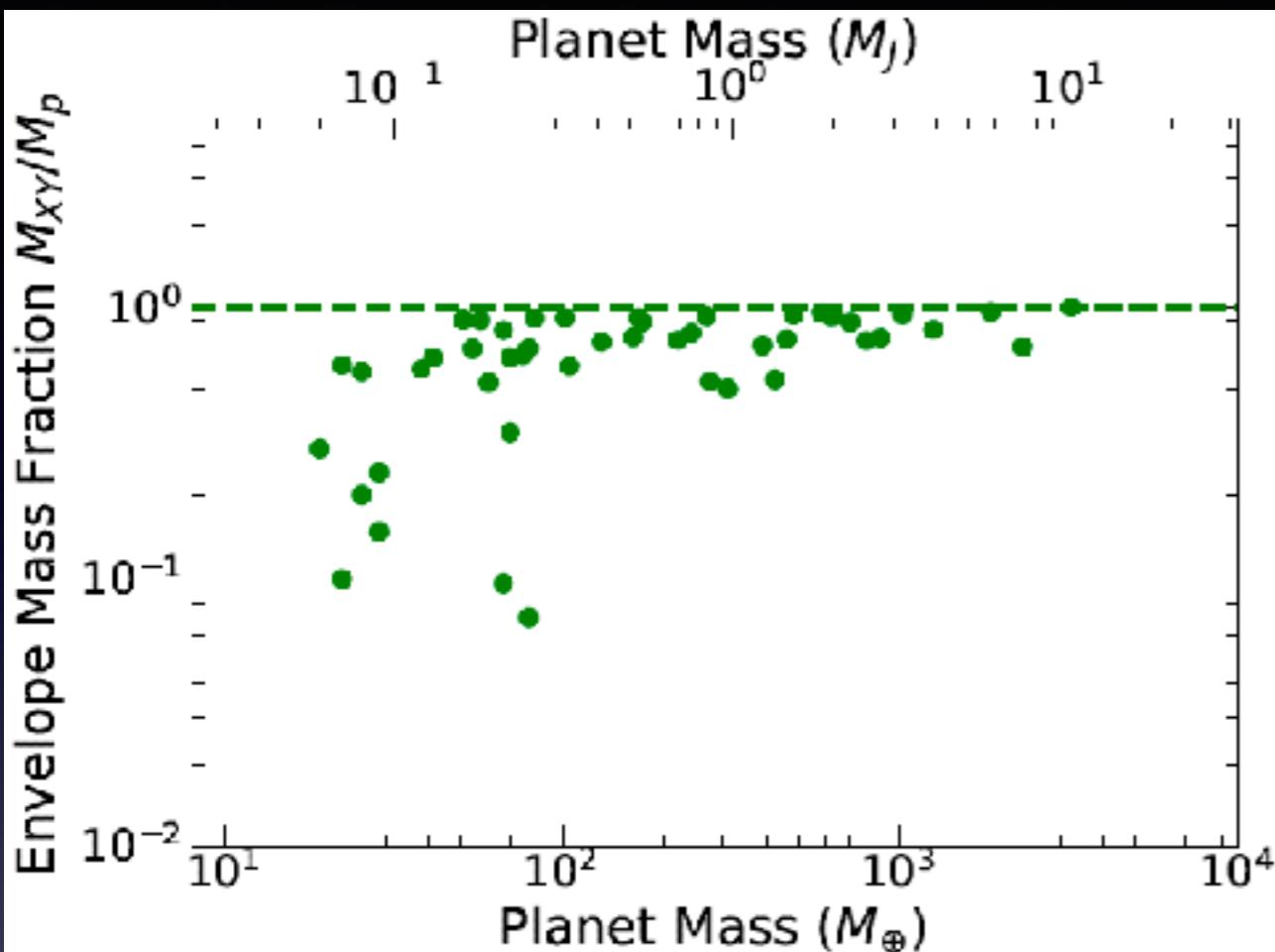
$$M_Z = \cancel{M_{core}} + \cancel{M_{pl}} + \cancel{M_{pe}} + \cancel{M_{Z,gas}}$$

Planets

Pebbles

dust in gas

Critical core mass and runaway gas accretion



$$M_p = M_{XY} + M_Z$$

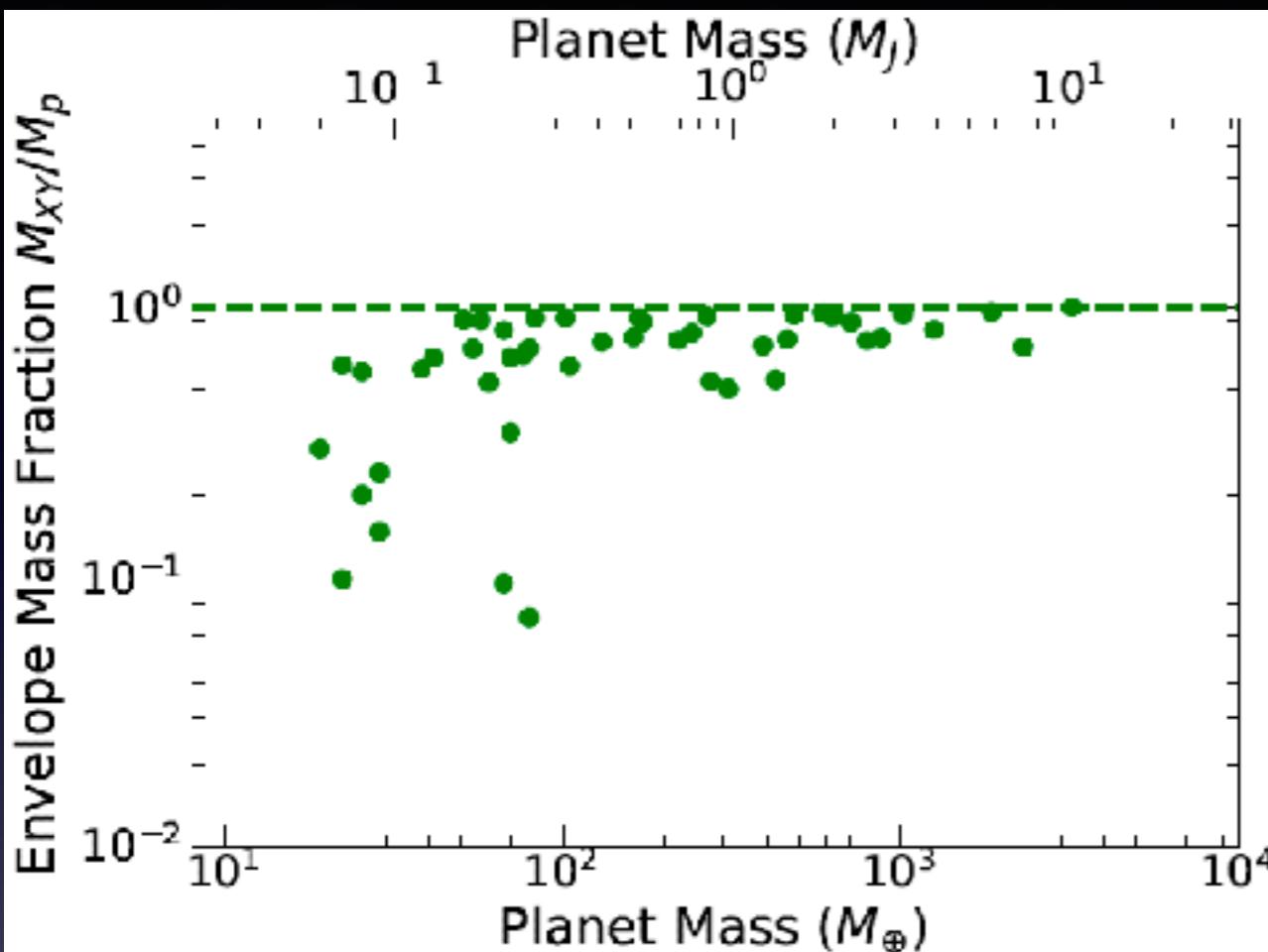
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Planetesimals

Pebbles

dust in gas

Critical core mass and runaway gas accretion



Runaway gas accretion occurred for planets with $M_p > 100M_\odot$

$$M_p = M_{XY} + M_Z$$

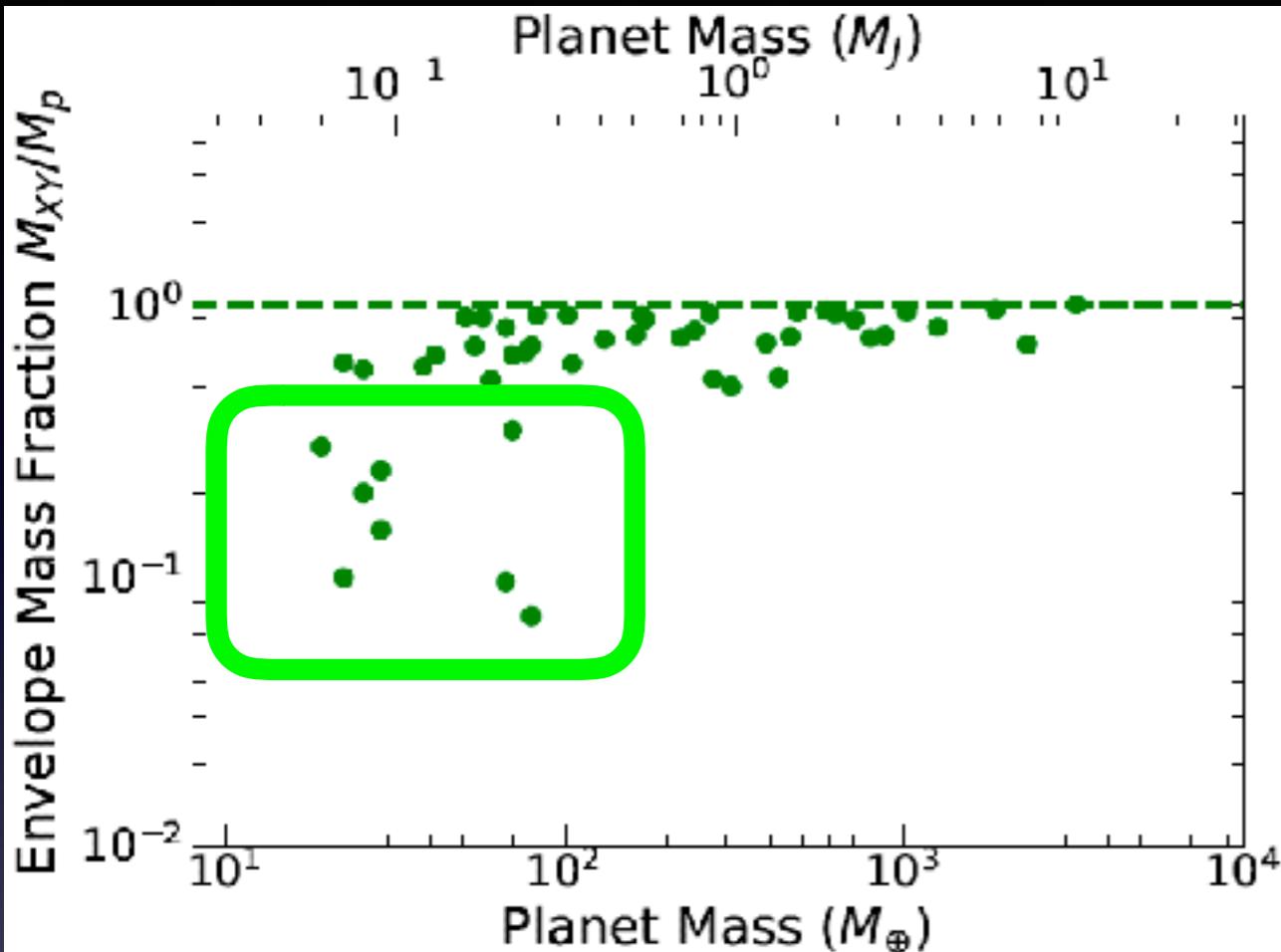
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Planetsimals

Pebbles

dust in gas

Critical core mass and runaway gas accretion



Runaway gas accretion occurred for planets with $M_p > 100 M_{\odot}$

Some mechanisms are needed for some exoplanets to avoid runaway gas accretion

$$M_p = M_{XY} + M_Z$$

$$M_Z = \cancel{M_{core}} + \cancel{M_{pl}} + \cancel{M_{pe}} + \cancel{M_{Z,gas}}$$

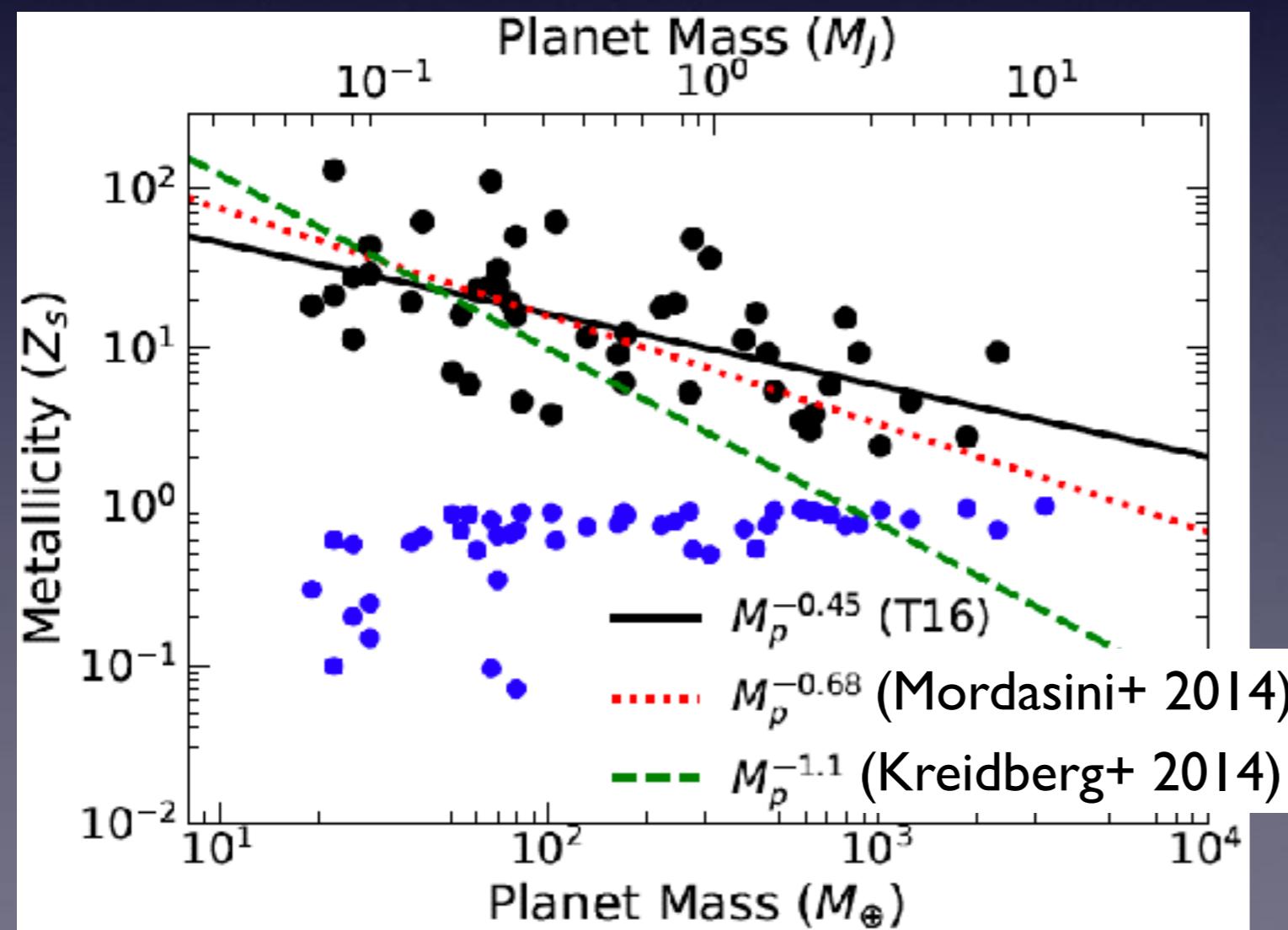
Planетесimals

Pebbles

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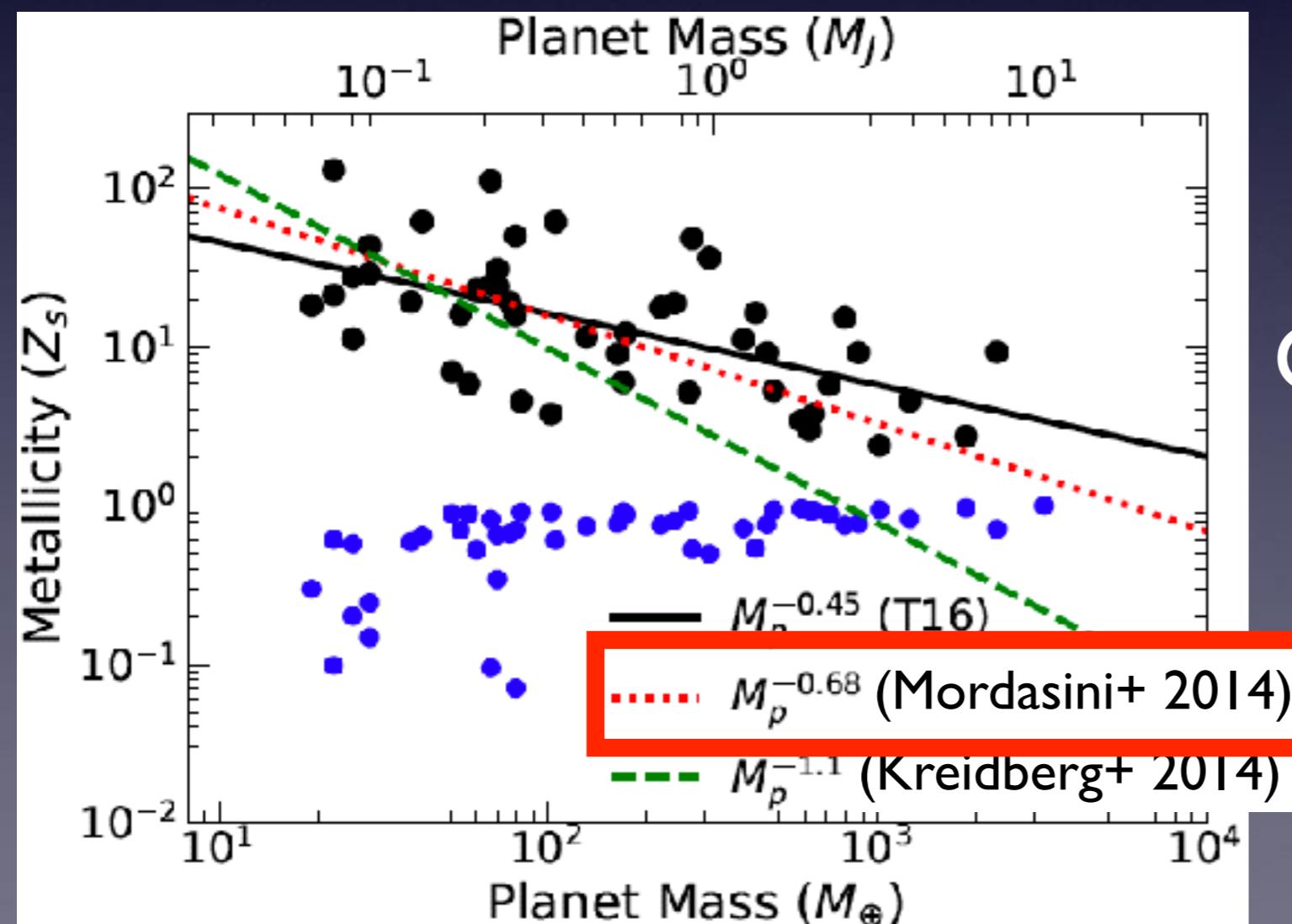
Gas accretion is limited by disk evolution, following Tanigawa & Ikoma 2007



Comparison with previous studies

Power-law index	T16	M_{core}	$M_{pl} (\text{w/o Gap})$	$M_{pl} (\text{w/ Gap})$	M_{pe}
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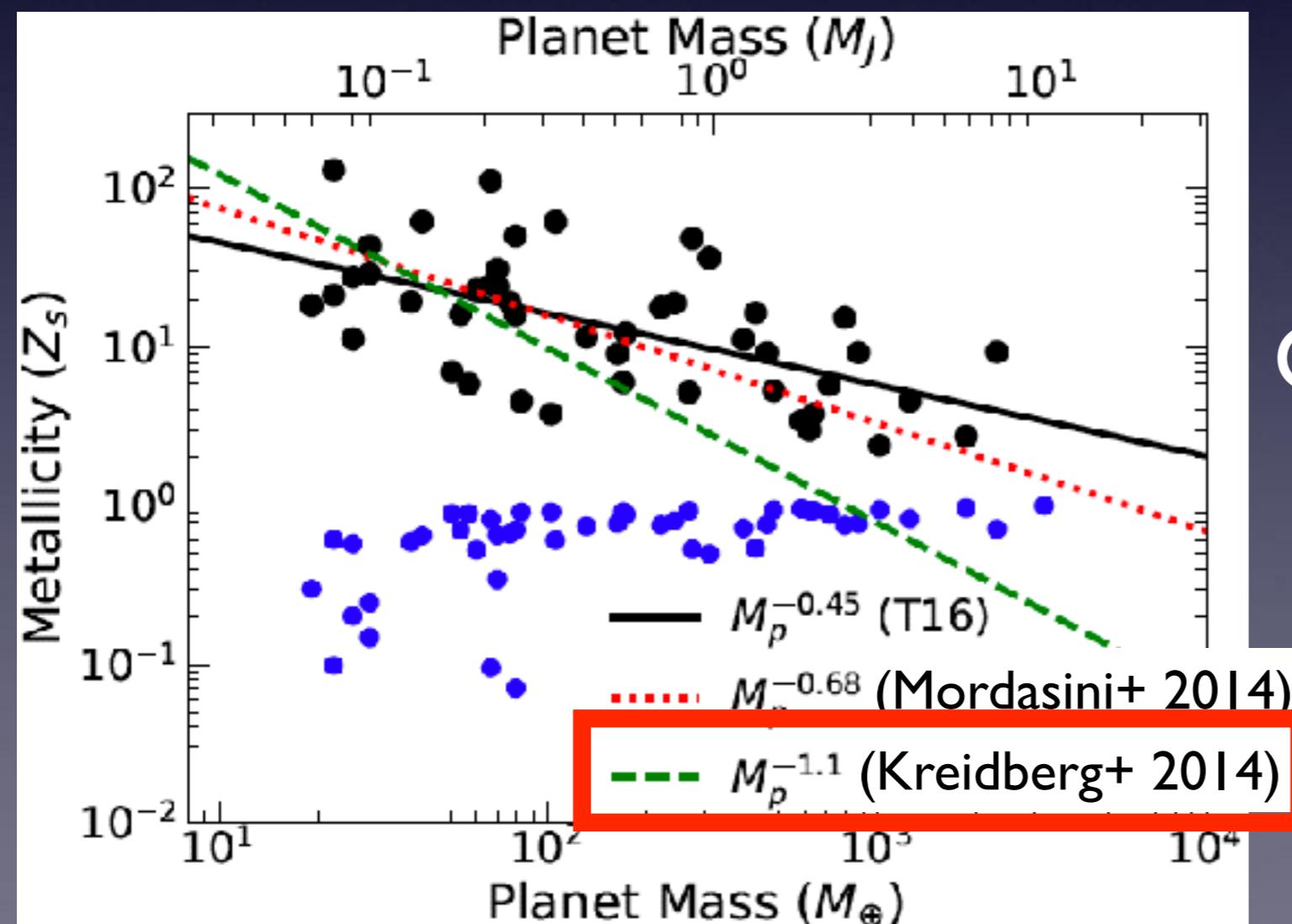


Comparison with previous studies

Our model can reproduce the results of Mordasini

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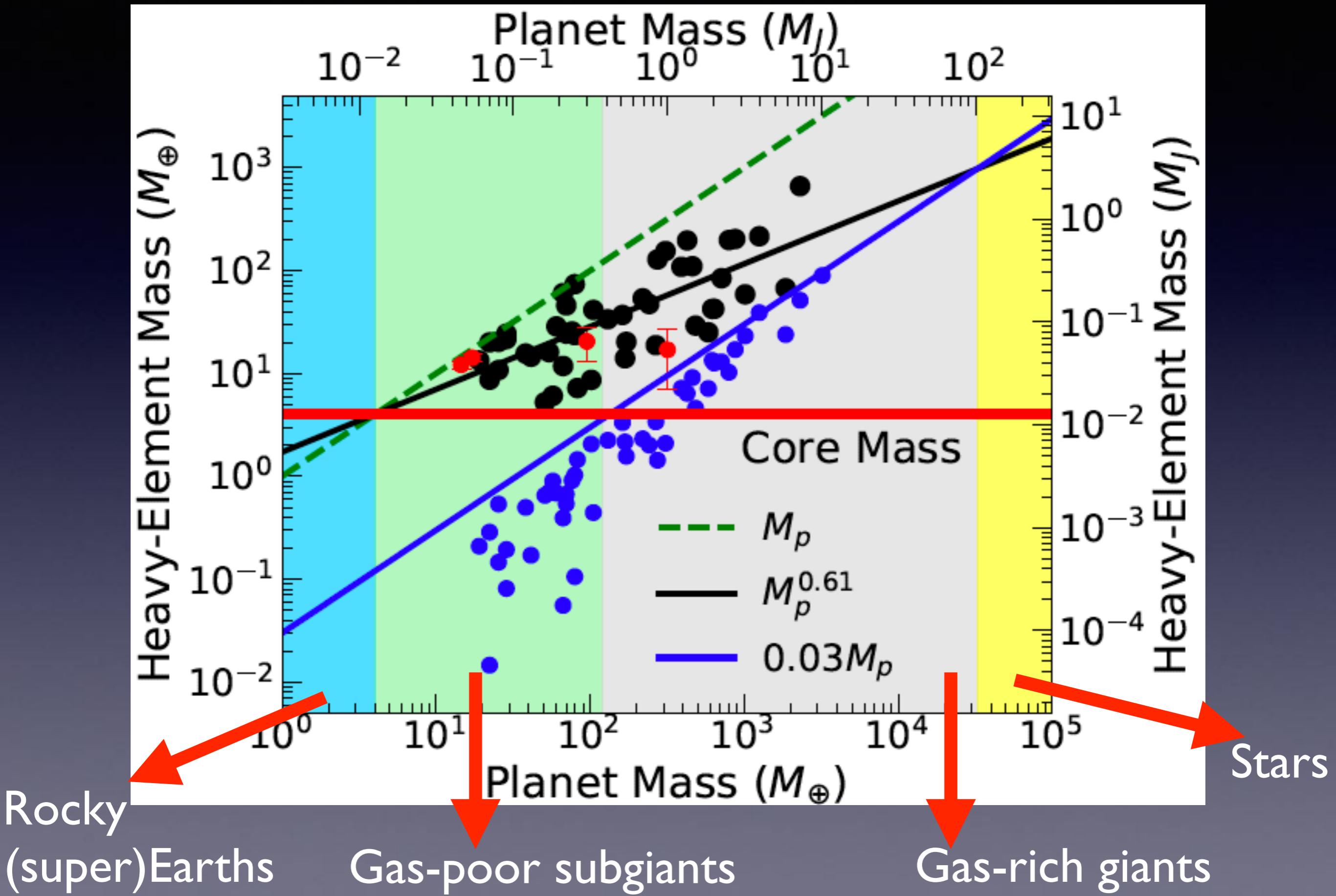


Comparison with previous studies

Our model can reproduce the results of Mordasini

Evolution of atmospheric metallicities in exoplanets can be explored

Classification of observed exoplanets



Summary

Hasegawa et al. 2018, ApJ, 865, 32

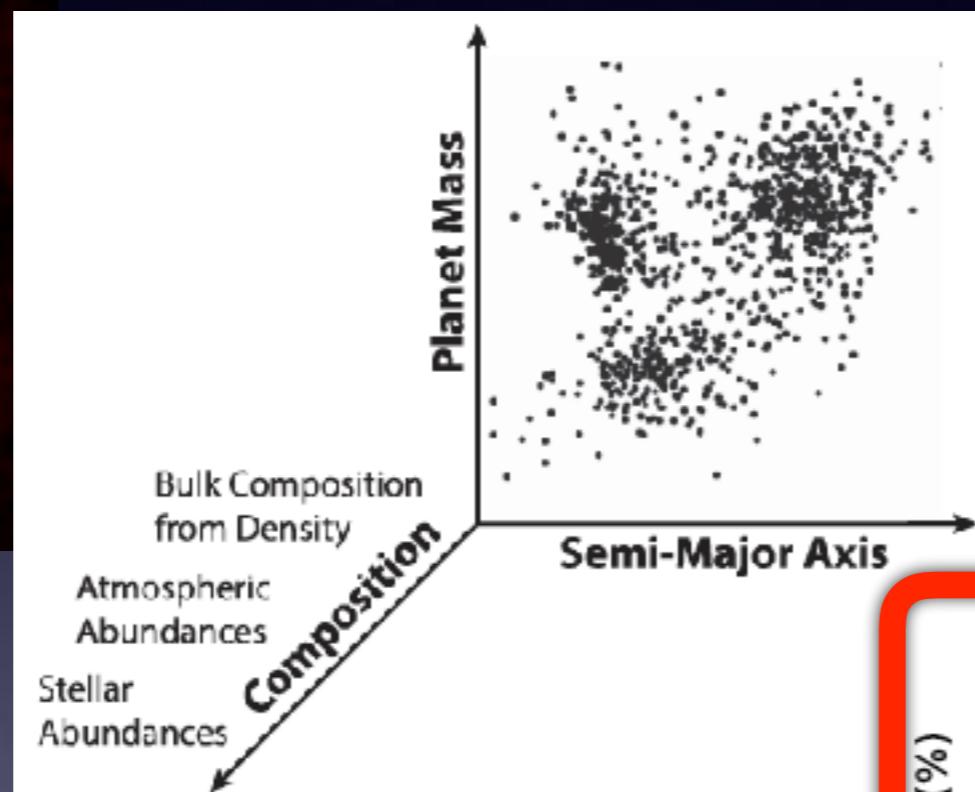
- Observed warm Jupiters tend to have correlations:

$$M_Z \propto M_p^{3/5} \quad \frac{Z_p}{Z_s} = \frac{M_Z}{M_p} \frac{1}{Z_s} \propto M_p^{-2/5}$$

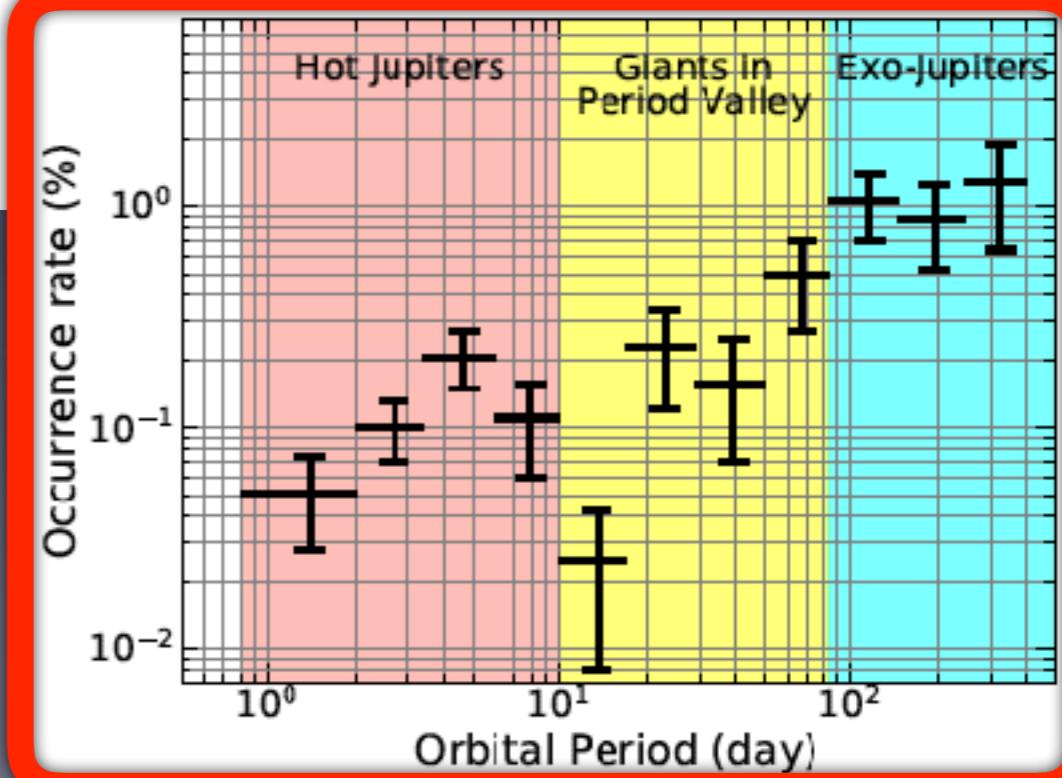
- We show that accretion of solids from **gapped planetesimal** disks can reproduce the above trends better
- Our results indicate that core formation, pebble accretion, and dust accretion accompanying gas accretion are **not** important
- Runaway gas accretion is **avoided** for some planets with mass of $M_p \simeq 20 - 100 M_\oplus$
- Our analysis can **reproduce** the results of detailed population synthesis calculations (Mordasini et al 2014)
- Our results suggest that evolution of **atmospheric metallicities** can be explored in the $Z_p - M_p$ diagram

New Disk Model

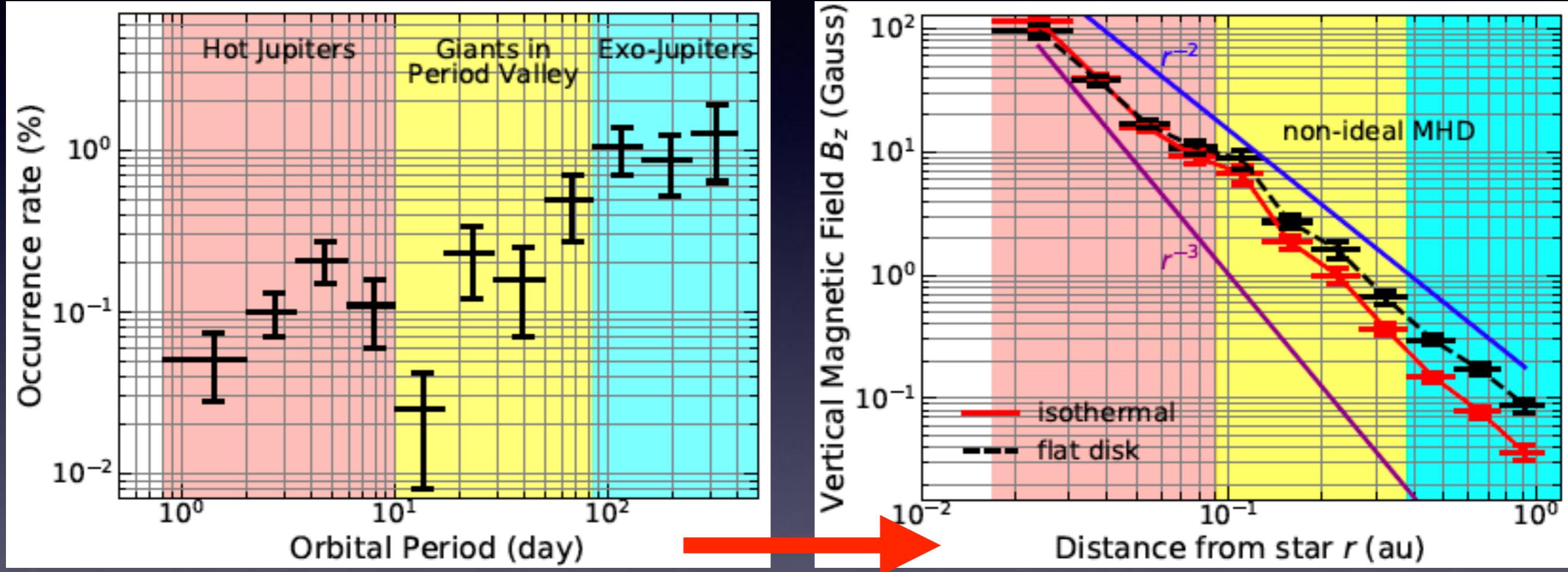
Composition of planets



Retrieval approach

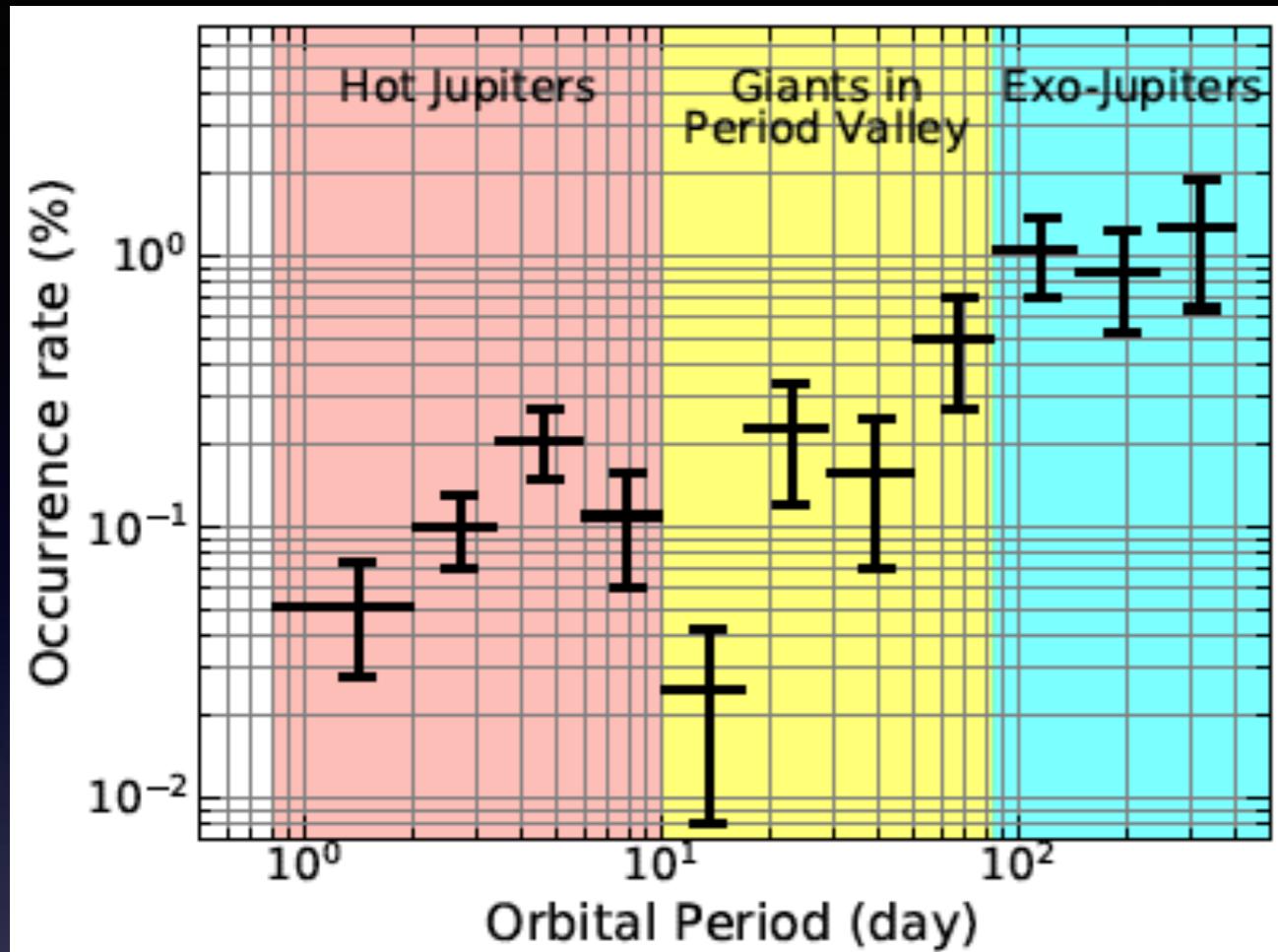


Close-in Giant Planets via In-situ Gas Accretion & Their Natal Disk Properties

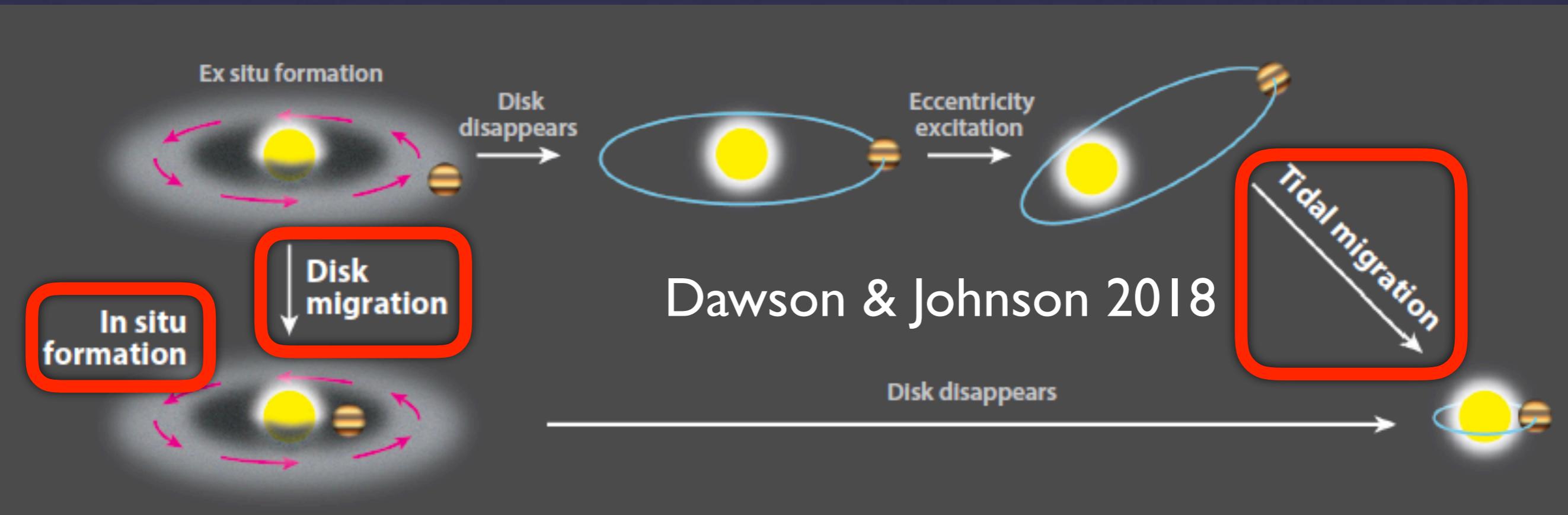


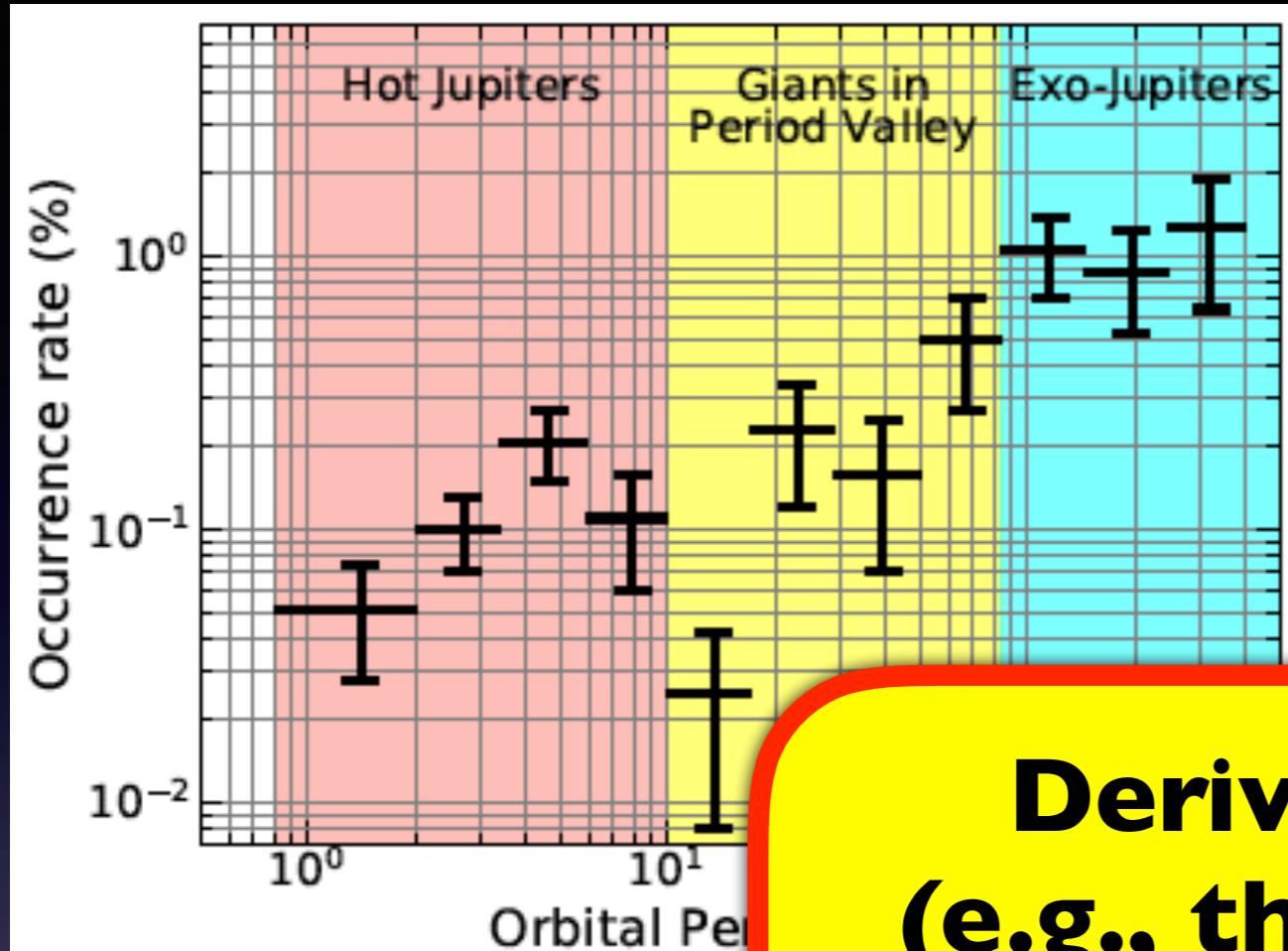
Santerne et al 2016

in collaboration with
Mathew Yu (UCLA) and Brad Hansen (UCLA)



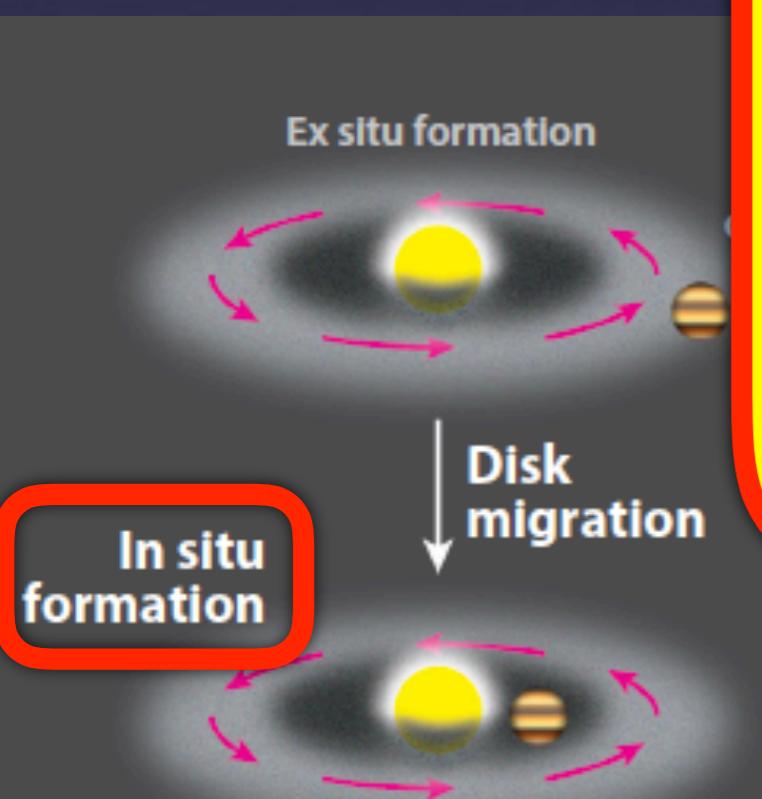
How to form close-in gas giants?





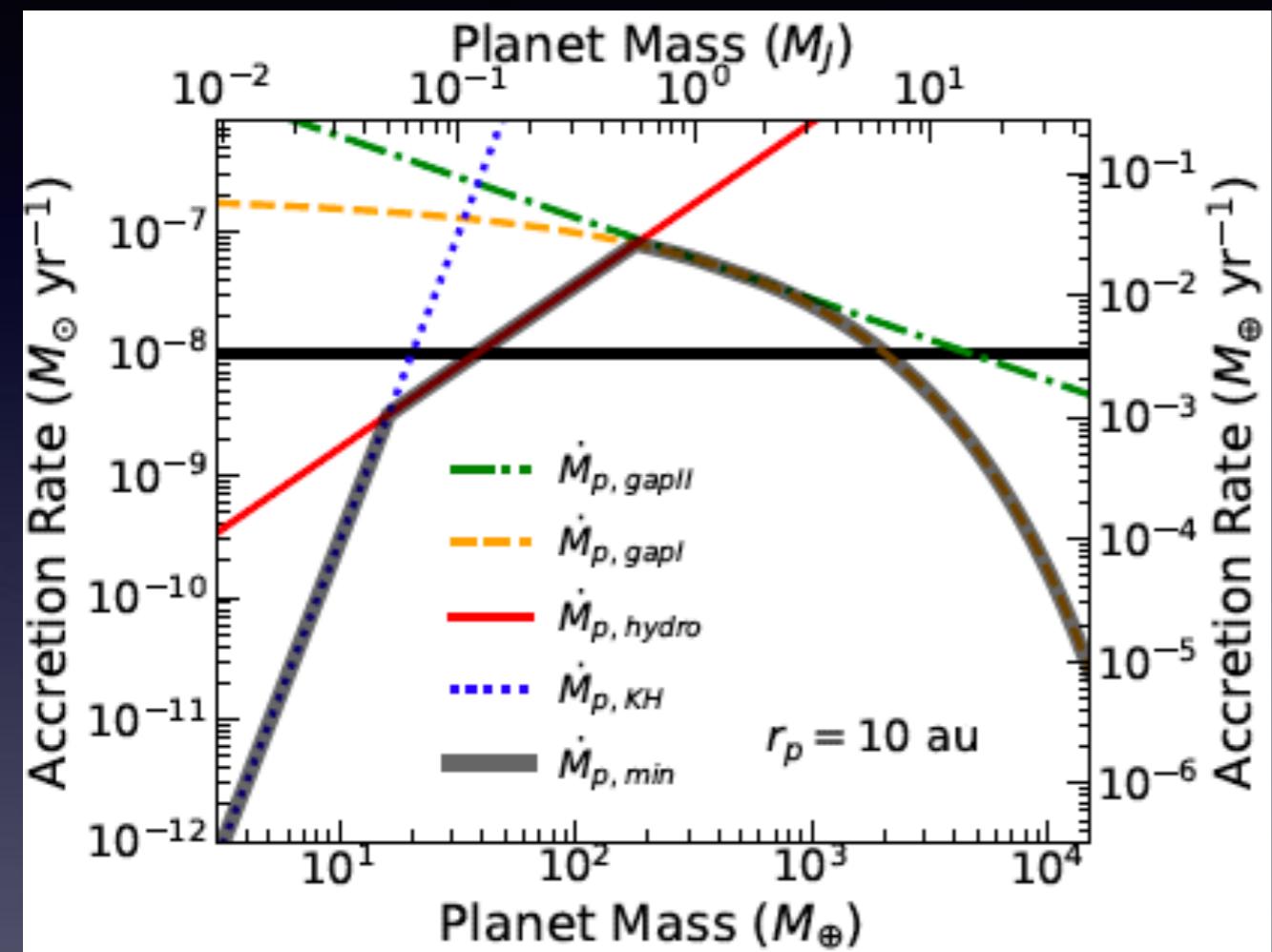
How to form close-in gas giants?

**Derive some observables
(e.g., the gas surface density)
from
the observed occurrence rate
distribution under
the in-situ gas accretion scenario**



Basic Hypothesis:
the occurrence rate \sim gas accretion onto planets

Basic Hypothesis: the occurrence rate \sim gas accretion onto planets



Hasegawa et al 2019a, submitted

Gas accretion
Kelvin-Helmholtz contraction
Disk-limited accretion
Accretion through gas gaps

Basic Hypothesis:
the occurrence rate \sim gas accretion onto planets

$$\dot{M}_p \simeq 0.29 \left(\frac{H_g}{r_p} \right)^{-2} \left(\frac{M_p}{M_*} \right)^{4/3} \Sigma_g r_p^2 \Omega$$

Tanigawa & Ikoma 2007

Gas accretion

Kelvin-Helmholtz contraction



Disk-limited accretion



Accretion through gas gaps

the occurrence rate $\propto \dot{M}_p \equiv f(T_d, \Sigma_g)$

Steady State Disk Accretion Model

Disk accretion rate: $\dot{M}_d = 3\pi\nu\Sigma_g$

Turbulent viscosity: $\nu = \alpha H_g^2 \Omega$ Shakura & Sunyaev 1973

Disk temperature: $T_d^4 = \frac{27\tau}{128\sigma_{SB}} \Sigma_g \nu \Omega^2$ Ruden & Lin 1986

The metal grain case

The case of evaporation
of metal grains

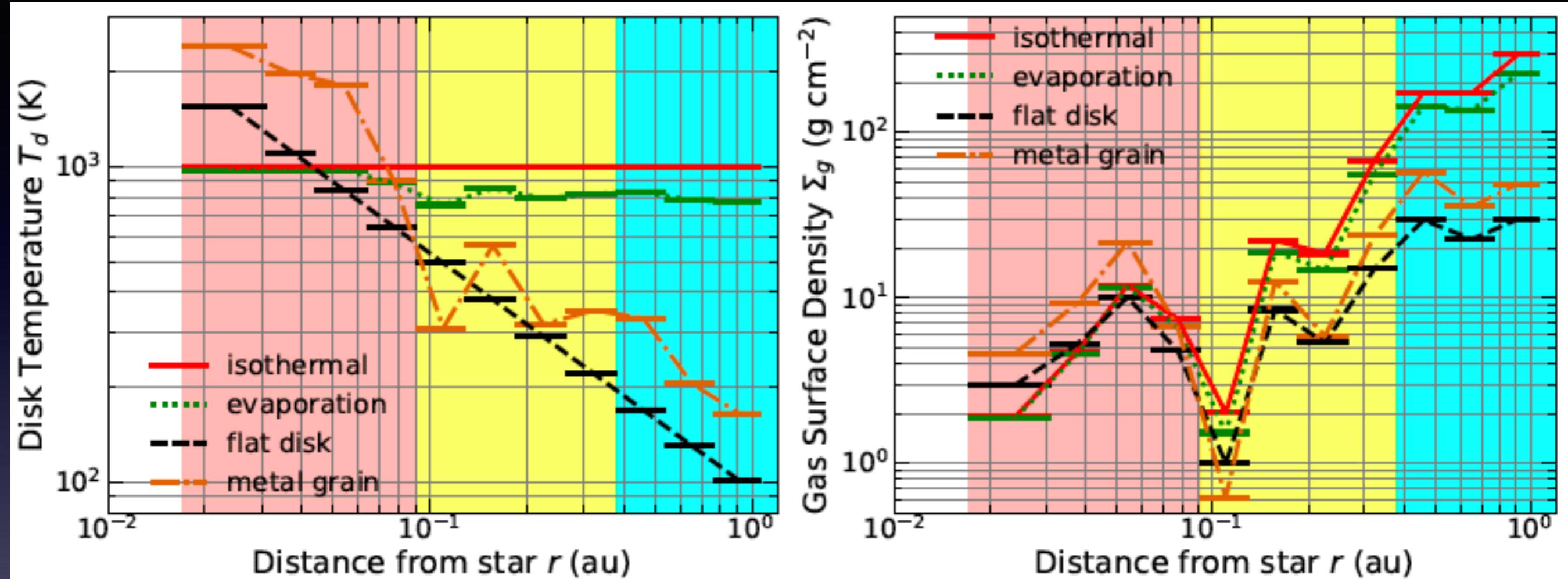
Bell et al 1997

Opacity:

ANALYTIC ROSSELAND MEAN OPACITY IN (cm ² g ⁻¹): $\kappa = \kappa_n \rho^{\alpha_n} T^{\beta_n}$.					
n	κ_n	α_n	β_n	Max. Temp. (K)	Reference
1.....	1×10^{-4}	0	2.1	132	HS
2.....	3×10^0	0	-0.01	170	HS
3.....	1×10^{-2}	0	1.1	375	HS
4.....	5×10^4	0	-1.5	390	HS
5.....	1×10^{-1}	0	0.7	580	HS
6.....	2×10^{15}	0	5.2	690	HS
7.....	2×10^{-2}	0	0.8	960 ^a	HS
8.....	2×10^{81}	1	-24	1570 ^a	BL
.....	1×10^{-1}	-0.7	-	2750	BL

$\Sigma_g \propto f(\text{Occurrence rate})$

Results: Disk Properties

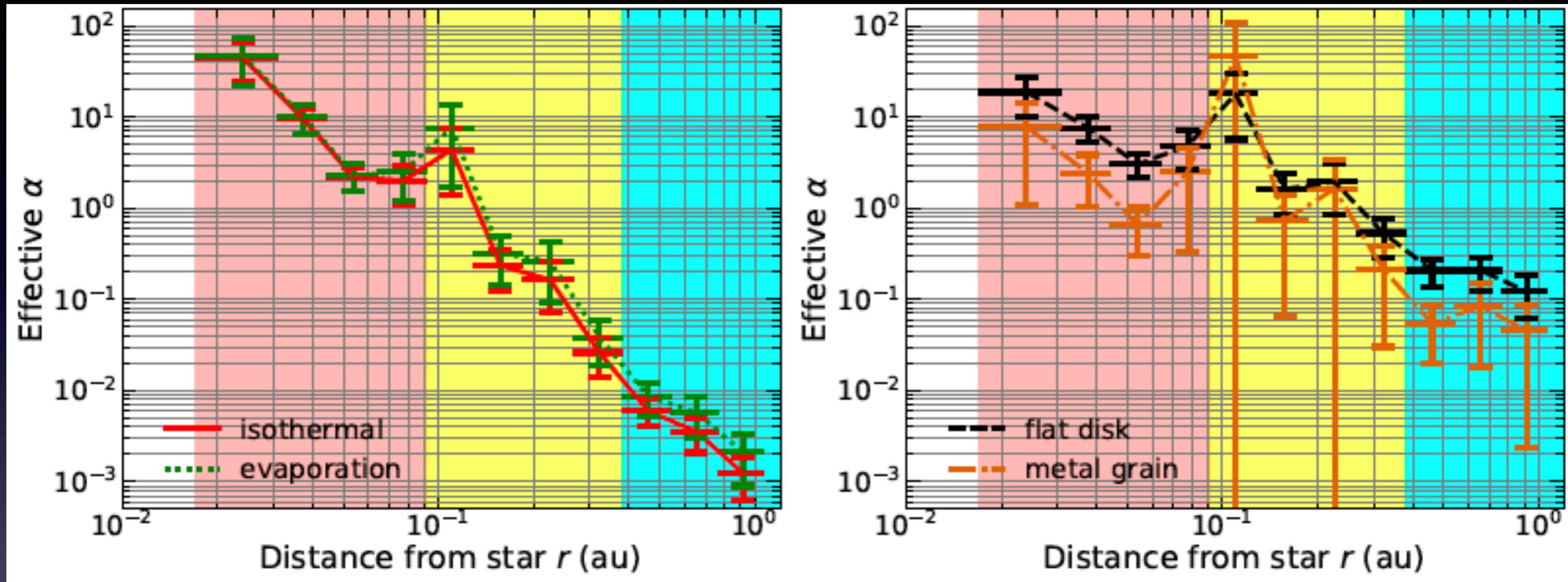


The evaporation case is well represented by the isothermal case

The metal grain case is well represented by the flat disk case

Gas surface density increases with increasing the distance from the central star (cf. Minimum-mass solar nebula $\propto r^{-3/2}$)

Results: Disk Properties



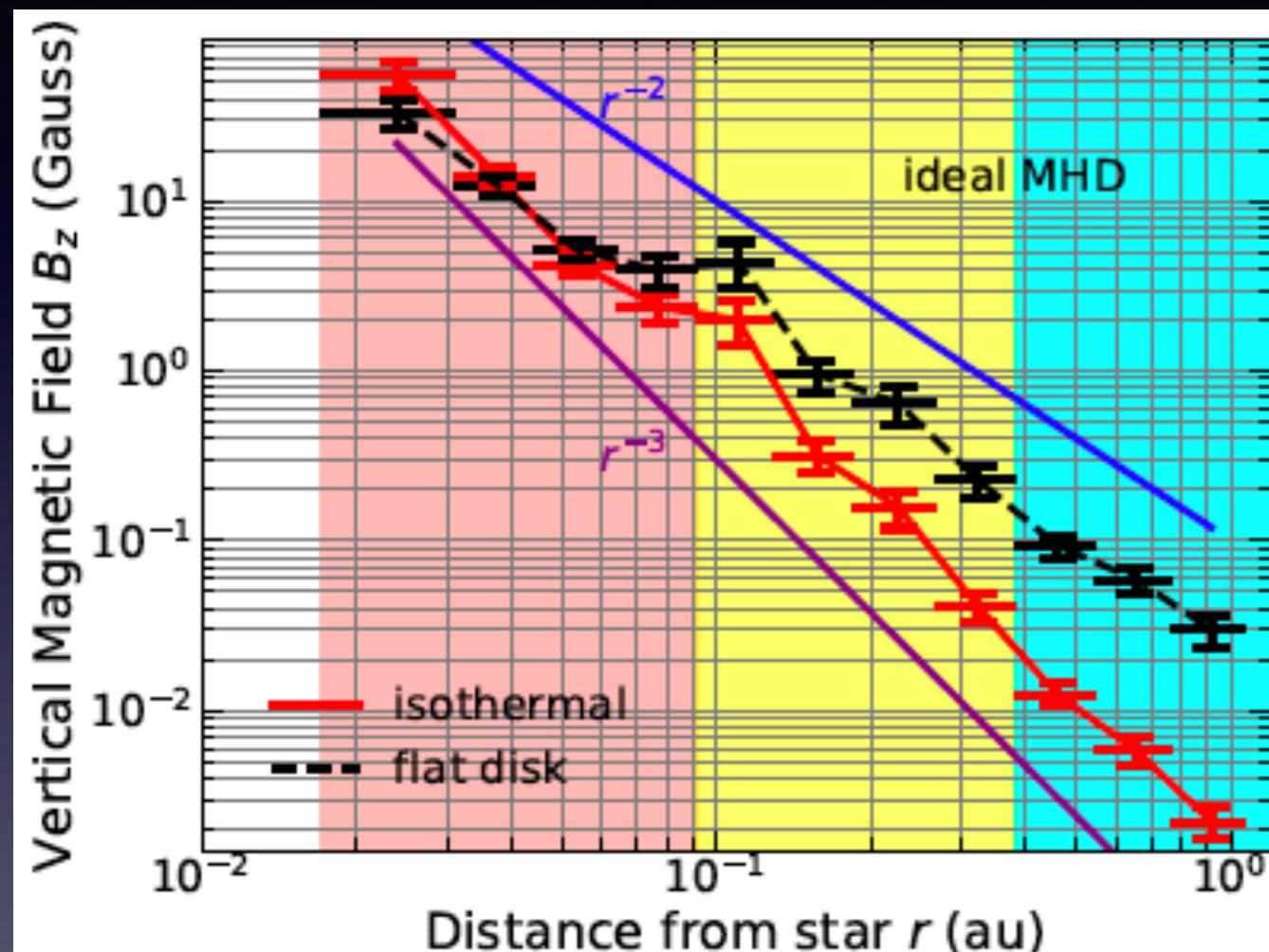
The evaporation case is well represented by the isothermal case

The metal grain case is well represented by the flat disk case

The effective alpha is inversely proportional to
the gas surface density, as expected

Results: Magnetic Field Profiles from $\beta_z = \frac{\rho_g c_s^2}{B_z^2 / 8\pi}$

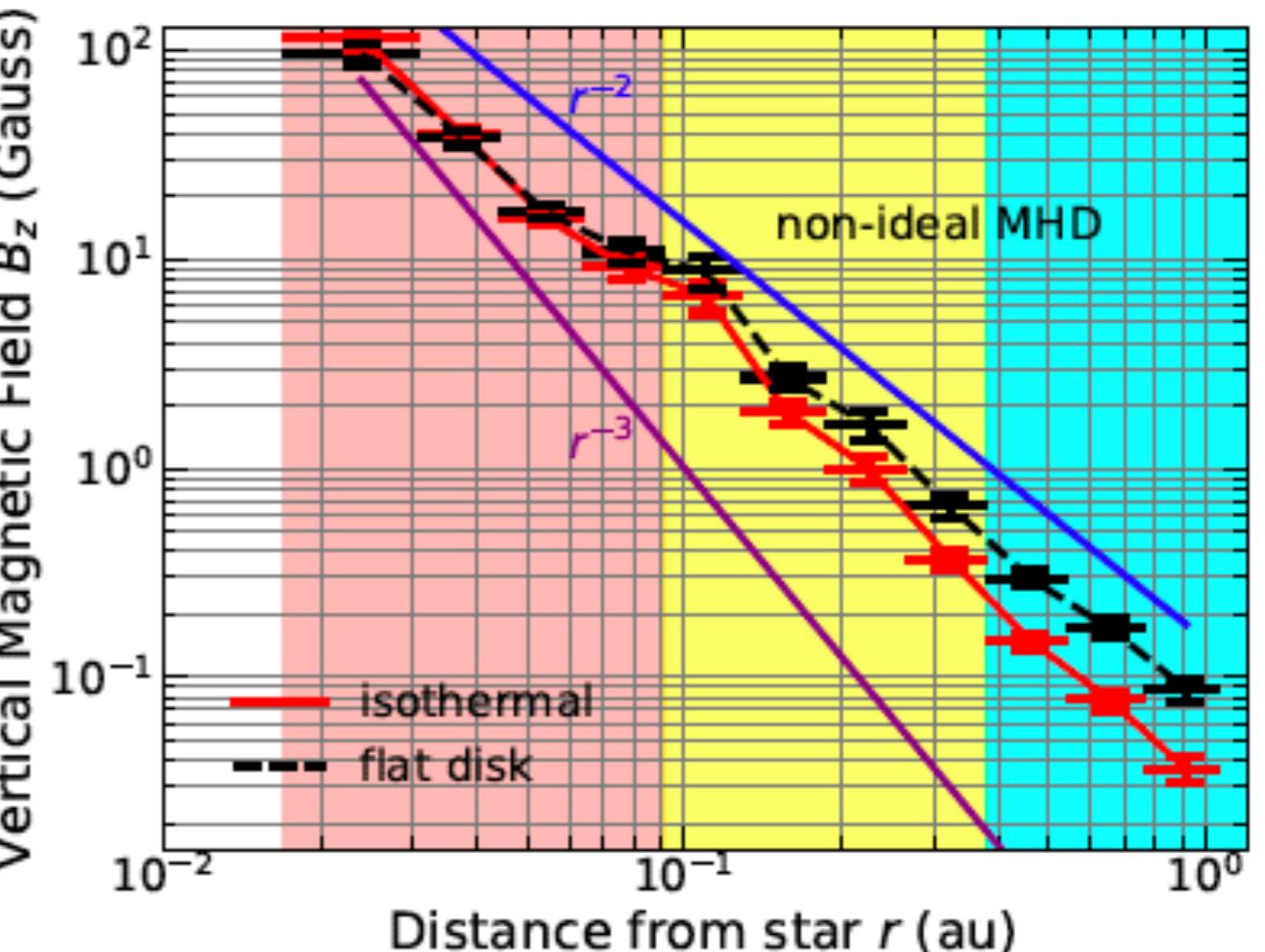
ideal MHD case



$$\alpha_{\text{ideal}} = 11\beta_z^{-0.53}$$

Salvesen et al 2016

non-ideal MHD case

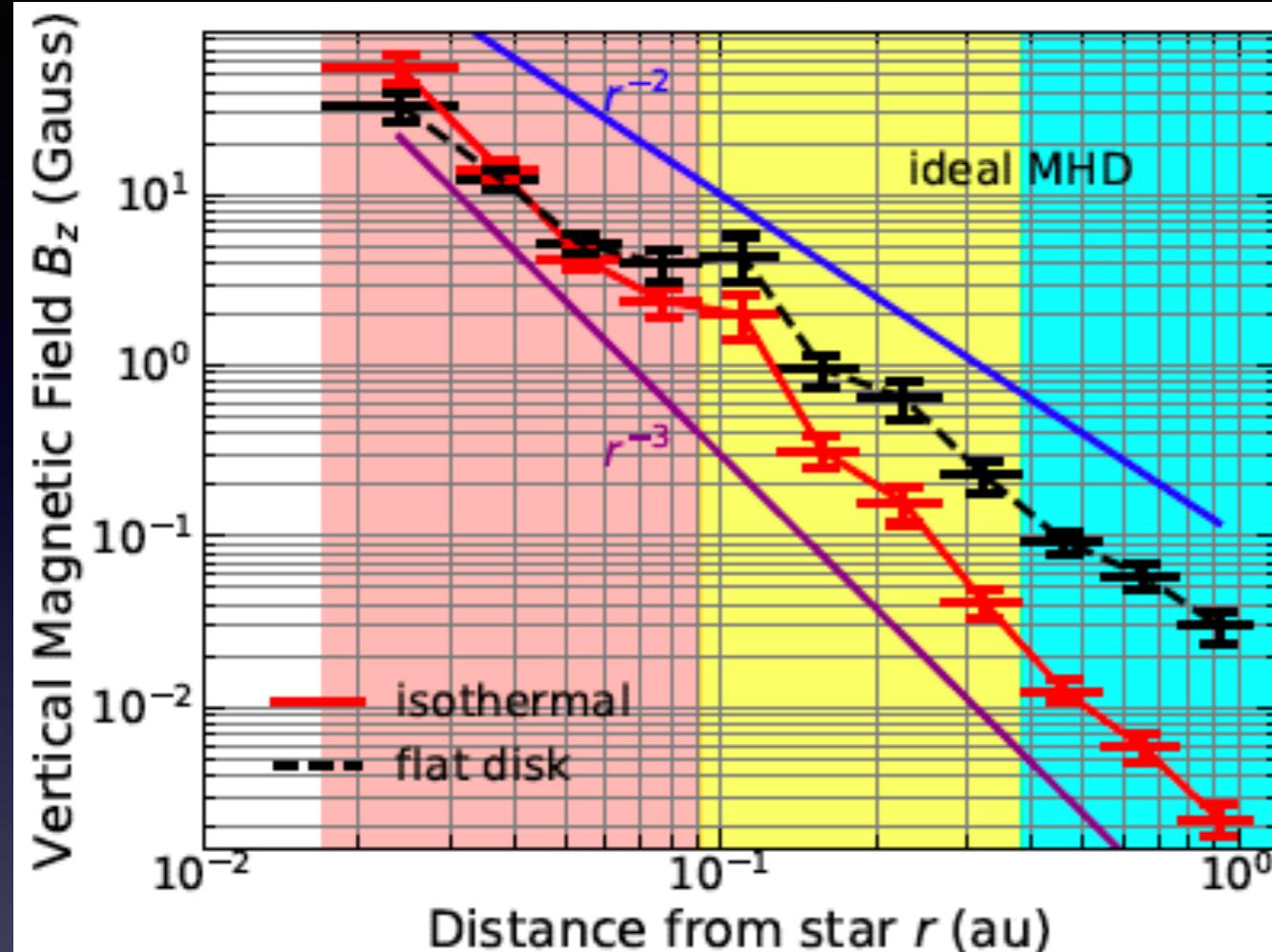


$$\alpha_{\text{non-ideal}} = \frac{4r}{3\sqrt{\pi}H_g} W_{z\phi}$$

$$W_{z\phi} = 0.23 \left(\frac{r}{1\text{au}} \right)^{0.46} \beta_z^{-0.66}$$

Bai 2013

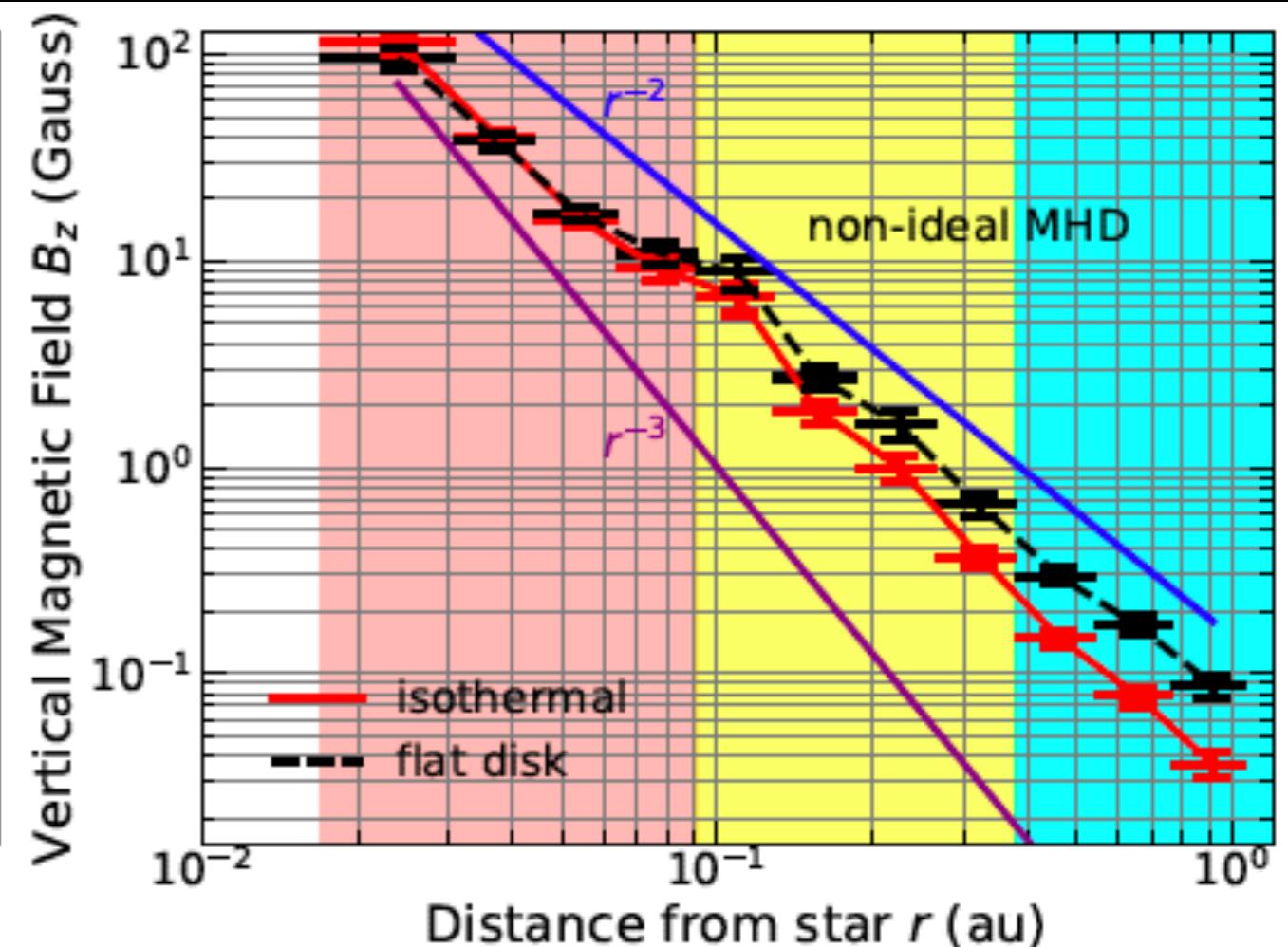
Implications



Stellar dipole fields

$$B_s \sim 10^3 \left(\frac{r}{1.5R_\odot} \right)^{-3} \text{ G}$$

$$\sim 41 \left(\frac{r}{2 \times 10^{-2} \text{ au}} \right)^{-3} \text{ G}$$



Large-scale disk fields

$$B_d \sim 0.1 \left(\frac{r}{1 \text{ au}} \right)^{-2} \text{ G}$$

Okuzumi et al 2014

Summary

Hasegawa et al, 2019b, submitted ApJL

- The origin of close-in giant planets is still unclear
- The occurrence rate distribution has some intriguing structure
- Developed the simple, semi-analytical model under the hypothesis that the occurrence rate distribution may reflect gas accretion rates onto protoplanets
- The gas surface density increases with increasing the distance from the central star (cf. MMSN model)
- The occurrence rate distribution may trace the magnetic field profile - stellar dipole fields dominate at $r < 0.1$ au and the large scale field may be important at $r > 0.1$ au

Chondrules: the primitive material formed in the Solar Nebula (disk)



Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of important advances in planet formation thanks to astonishing observations
- As examples, theoretical modeling of the HL Tau disk, the origin of heavy elements in observed exoplanets, and the origin of close-in planets via in-situ gas accretion are discussed
- further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems